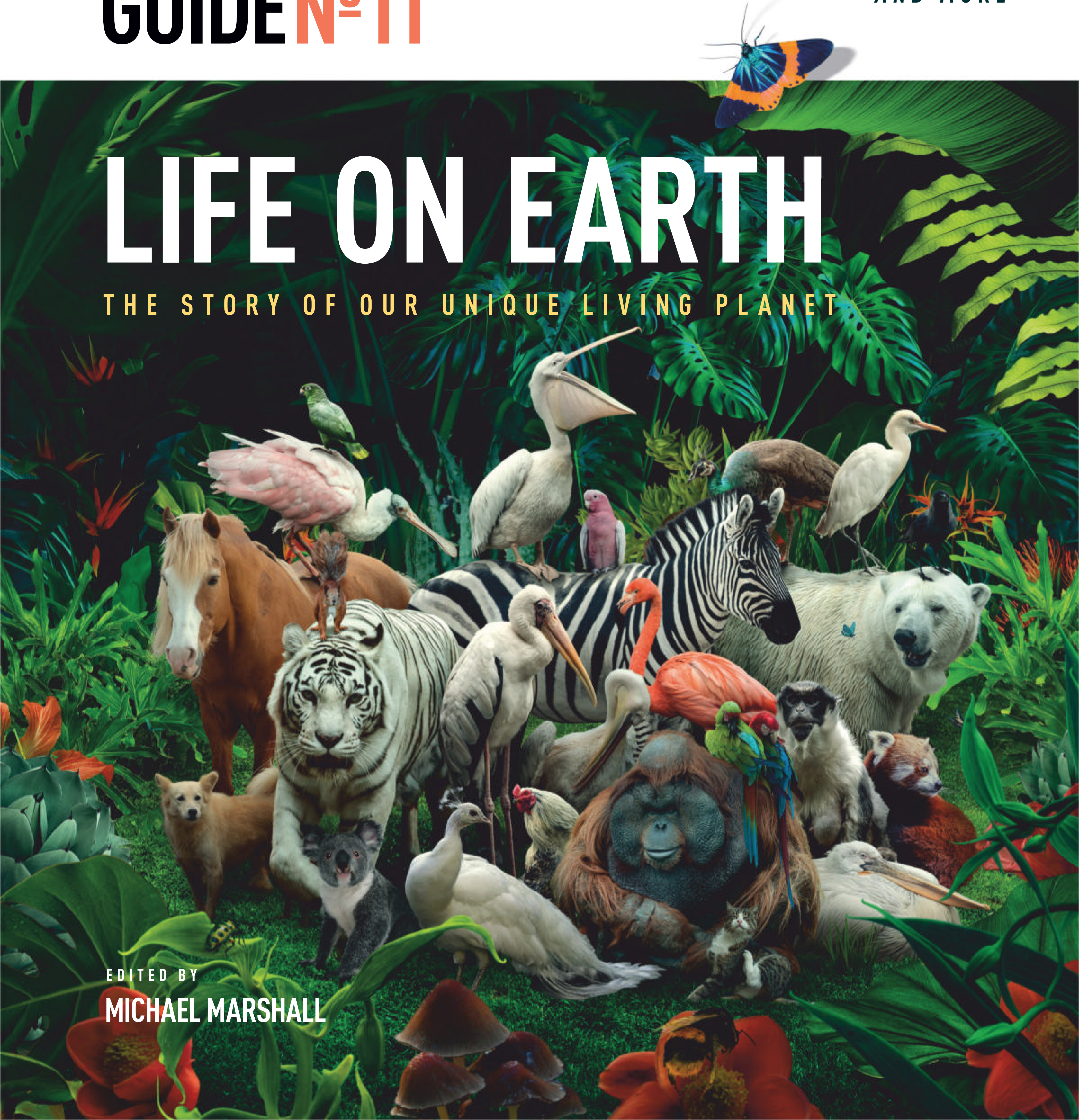
New Scientist

ESSENTIAL GUIDE Nº11

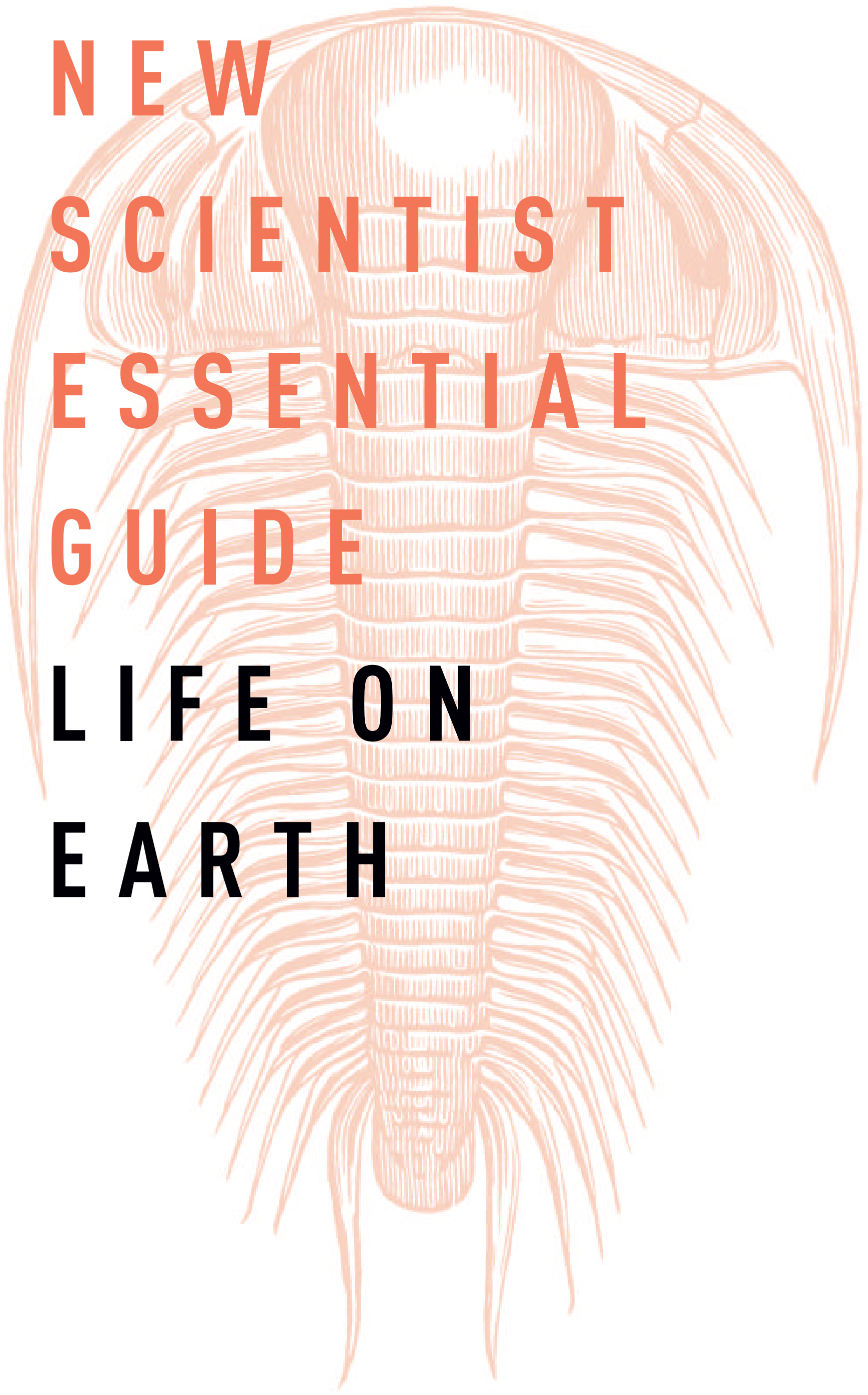
HOW LIFE BEGAN
THE WORLD OF MICROBES
ORIGINS OF COMPLEX LIFE
ANIMALS, PLANTS AND FUNGI
EARTH'S MASS EXTINCTIONS
BIODIVERSITY UNDER THREAT
AND MORE



LIFE ON EARTH

THE STORY OF OUR UNIQUE LIVING PLANET

EDITED BY
MICHAEL MARSHALL



NEW SCIENTIST ESSENTIAL GUIDE

LIFE ON EARTH

THE world in which we live is the most extraordinary place in the known universe. In all the glittering profusion of celestial bodies, Earth is the only planet we know of that harbours life: birds winging through the sky, insects scurrying on the ground, tiny shrubs and towering trees, and all around us the countless invisible microorganisms that sustain the biosphere.

In this latest *New Scientist Essential Guid*e, we explore how we got here, starting from the very origin of life right through to the evolution of the complex organisms we see on the planet today.

But while the living world is precious, it is also threatened – mostly by our activities. In the final chapter, we explore the biodiversity crisis, examine how many species are going extinct and ultimately set out a rescue plan for nature. The biosphere has supported our species throughout our existence: now it is time for us to help the biosphere in return.

I hope you enjoy following this fascinating storyof life on our planet. Feedback is welcome at essentialguides@newscientist.com, and previous editions in the series can be bought at shop.newscientist.com. *Michael Marshall*

NEW SCIENTIST ESSENTIAL GUIDES
NORTHCLIFFE HOUSE, 2 DERRY STREET,
LONDON, W8 5TT
+44 (0)203 615 6500

© 2022 NEW SCIENTIST LTD, ENGLAND

NEW SCIENTIST ESSENTIAL GUIDES
ARE PUBLISHED BY NEW SCIENTIST LTD
ISSN 2634-0151
PRINTED IN THE UK BY
PRECISION COLOUR PRINTING LTD AND
DISTRIBUTED BY MARKETFORCE UK LTD
+44 (0)20 3148 3333

COVER: VIZERSKAYA/ISTOCK
ABOVE: NASTASIC/ISTOCK

SERIES EDITOR Richard Webb
DESIGN Craig Mackie
SUBEDITOR Bethan Ackerley
PRODUCTION AND APP Joanne Keogh
TECHNICAL DEVELOPMENT (APP)
Amardeep Sian
PUBLISHER Nina Wright
EDITOR-IN-CHIEF Emily Wilson
DISPLAY ADVERTISING +44 (0)203 615 6456
displayads@newscientist.com

ABOUT THE EDITOR

Michael Marshall is a *New Scientist* consultant and author of *The Genesis Quest*

ADDITIONAL CONTRIBUTORS

Colin Barras, David Begun, Michael Benton, Jason Bittel, Riley Black, Lynne Boddy, Jonathan R. Goodman, Nick Higgs, Bob Holmes, Rowan Hooper, Lucas Joel, Richard Jones, Alice Klein, Nick Lane, Graham Lawton, Michael Le Page, Michael Marshall, James O'Donoghue, Penny Sarchet, Ibrahim Sawal, Richard Schiffman

CHAPTER 1
HOW DID LIFE BEGIN?

Earth is lush with thriving life. When it first formed, however, it was a sterile rock. How life on the planet first got started – and where – are fundamental questions about which few scientists agree.

p. 6 The cradle of life
p. 8 Did life come from space?
p. 10 Protein, genes or cells?
p. 12 Life’s power pack
p. 15 Out of the hydrothermal vent
p. 18 Did everything come first?

CHAPTER 2
SINGLE-CELLED LIFE

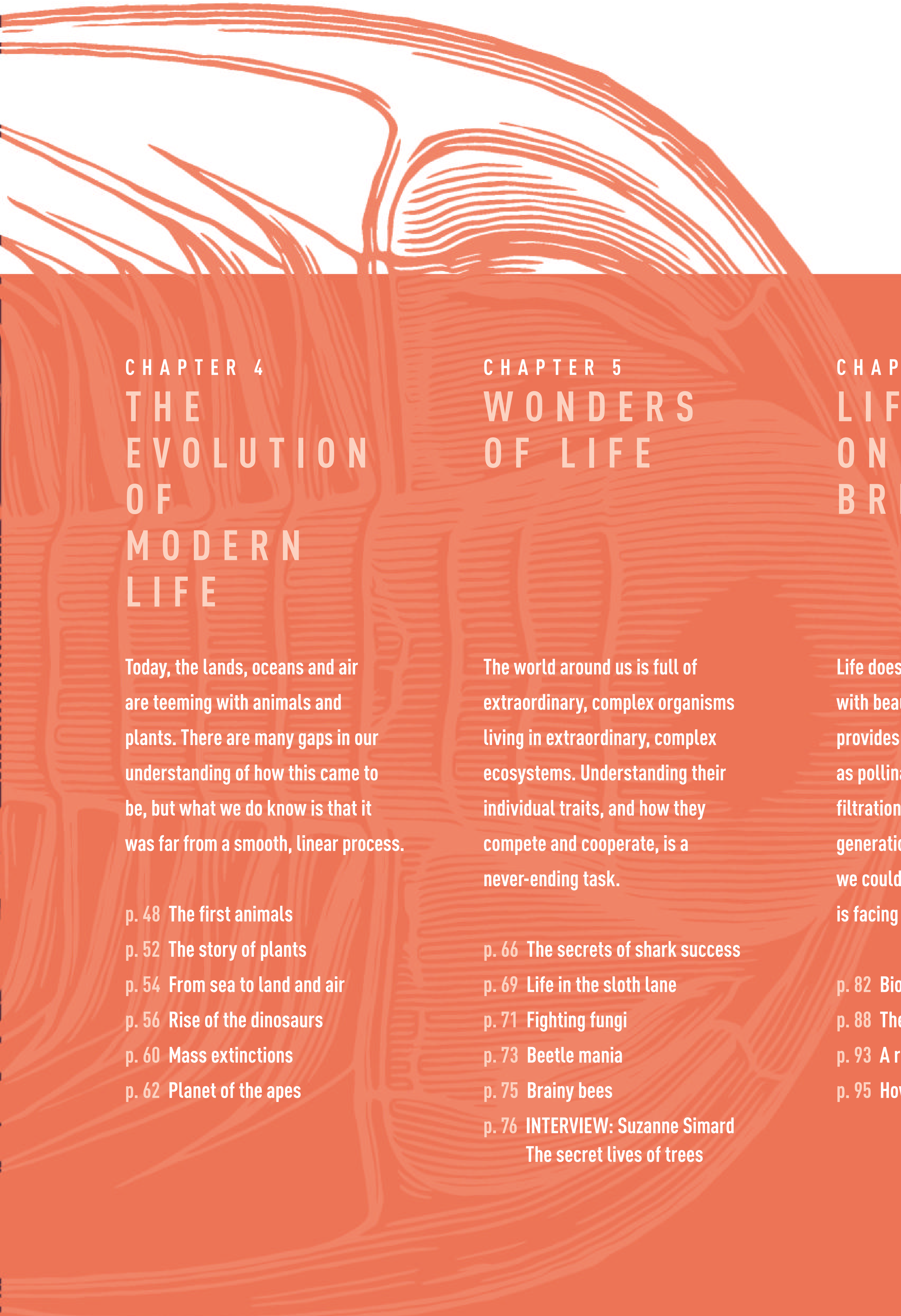
For most of our planet’s history, single-celled organisms have been all that existed. But in developing tricks such as photosynthesis to extract energy from their environment, they fundamentally changed the planet, creating the conditions for more complex life forms to evolve.

p. 24 On the origin of microbes
p. 25 A timeline of life
p. 28 The first photosynthesisers
p. 32 Viruses: Another kind of life
p. 35 Where did viruses come from?

CHAPTER 3
THE ORIGINS OF COMPLEX LIFE

Complex, macroscopic life forms such as animals, plants and fungi have crucial traits in common. They are built on complex, diversified, “eukaryotic” cells that work together – but how and why these innovations occurred remain mysteries.

p. 38 The first complex cells
p. 41 When did eukaryotes evolve?
p. 43 From one cell to many
p. 45 Beginnings of internal organs



CHAPTER 4

THE EVOLUTION OF MODERN LIFE

Today, the lands, oceans and air are teeming with animals and plants. There are many gaps in our understanding of how this came to be, but what we do know is that it was far from a smooth, linear process.

p. 48 The first animals
p. 52 The story of plants
p. 54 From sea to land and air
p. 56 Rise of the dinosaurs
p. 60 Mass extinctions
p. 62 Planet of the apes

CHAPTER 5

WONDERS OF LIFE

The world around us is full of extraordinary, complex organisms living in extraordinary, complex ecosystems. Understanding their individual traits, and how they compete and cooperate, is a never-ending task.

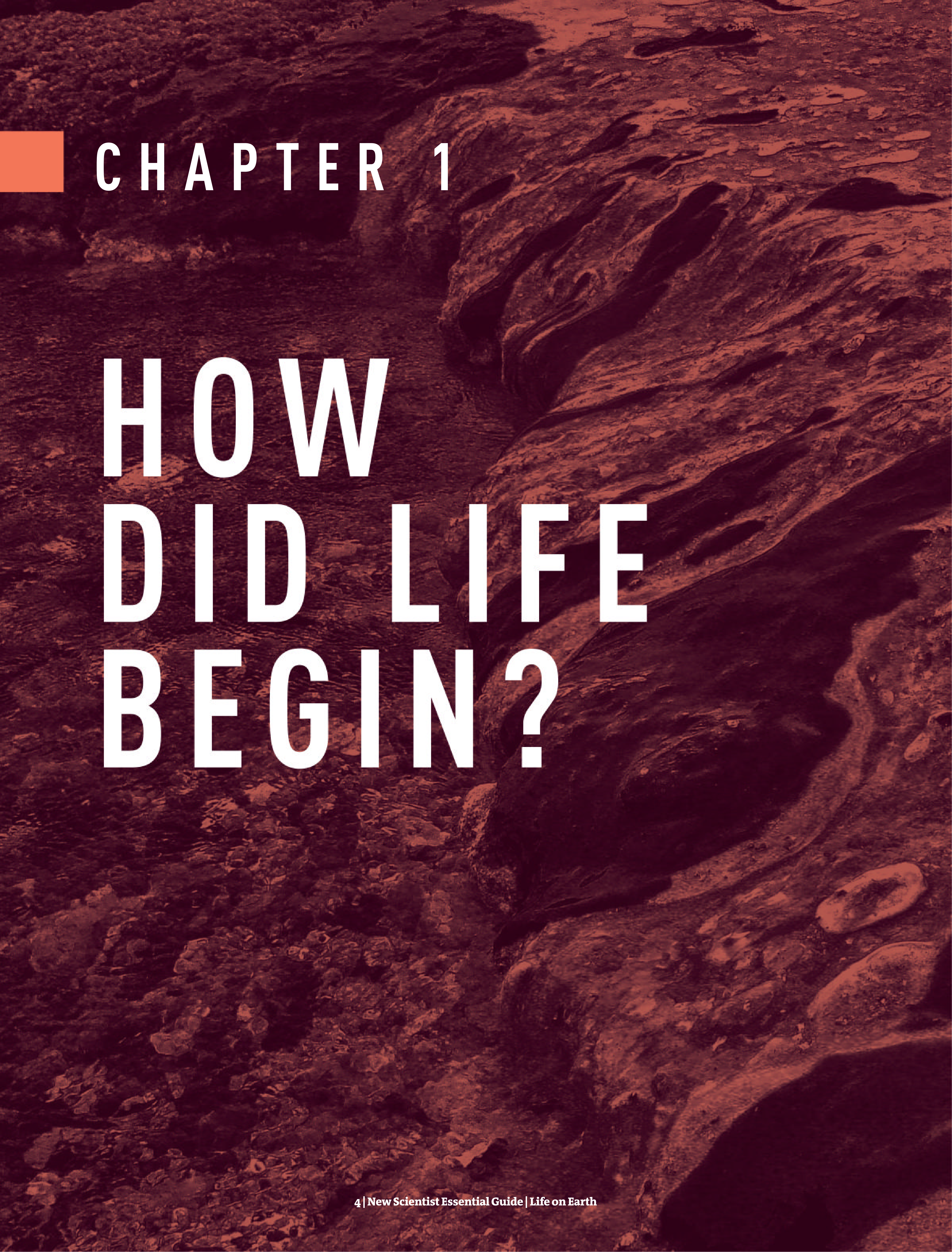
p. 66 The secrets of shark success
p. 69 Life in the sloth lane
p. 71 Fighting fungi
p. 73 Beetle mania
p. 75 Brainy bees
p. 76 INTERVIEW: Suzanne Simard The secret lives of trees

CHAPTER 6

LIFE ON THE BRINK

Life doesn't just adorn the world with beautiful things. It also provides ecosystem services, such as pollination, seed dispersal, water filtration, nutrient recycling, soil generation and so on, without which we couldn't function either. Now life is facing its greatest threat yet – us.

p. 82 Biodiversity in crisis
p. 88 The call of rewilding
p. 93 A rescue plan for nature
p. 95 How to restore an ecosystem



CHAPTER 1

HOW DID LIFE BEGIN?

Earth is lush with thriving life. When it first formed, however, it was a sterile rock. How did life first get started on our planet – and where?

These questions are among the most profound in science, and although many theories exist, scientists still can't agree on the answers. Which of life's key components – its proteins, its genes, its cell walls or its driving metabolism – came first? Did life emerge at a bubbling marine hydrothermal vent, in a warm pool on land or even in a dry or cold desert?

Getting to grips with the answers would help us grasp our place in the universe, and could even guide our search for life elsewhere.

THE CRADLE OF LIFE

The astounding innovation that was life must have arisen somewhere – somewhere that gave the right conditions for its rich chemistry to emerge and to be sustained. There are many contenders for the cradle of life, and arguments have long raged over which is the most promising.

CLINT FARLINGER/ALAMY STOCK PHOTO
PREVIOUS PAGE: ELIJAH LOVKOFF/ISTOCK PHOTO

CHARLES DARWIN kicked off the quest. In a letter he wrote to botanist Joseph Dalton Hooker in 1871, he described a hypothetical "warm little pond", rich in chemicals and salts, with sources of light, heat and electricity. He imagined that, in such an environment, proteins might spontaneously form, ready to turn into something more complex.

The first concrete idea about life's origins to capture scientists' attention bore similarities to Darwin's warm pond. It was the notion that when Earth was young, the oceans were filled with simple chemicals important for life, and that these would eventually self-assemble into simple living cells. This idea of a "primordial soup"was proposed in the 1920s by two researchers working independently: Alexander Oparin in the USSR and British geneticist J. B. S. Haldane.

The primordial soup hypothesis received dramatic support in 1953 when a young US graduate student named Stanley Miller, supervised by Nobel prizewinner Harold Urey, conducted a famous experiment. He mixed four simple chemicals – water, ammonia,

›

hydrogen and methane – in glass tubes, which were heated and shocked with electrical sparks to mimic lightning. The experiment made several amino acids, the building blocks of proteins. The Miller-Urey experiment showed, apparently, that the chemicals of life could form naturally.

Opinions remain divided as to how much the experiment actually tells us. Criticisms include that the "atmospheric" conditions Miller used in his tubes did not tally with the composition of Earth's atmosphere, although they might have been reproduced in certain parts of it. More recently, it has become clear that the borosilicate glass of the tubes themselves may have played a part in the reactions within – perhaps inadvertently reproducing the catalysing effect of silicate rocks on Earth's surface.

What we do now know, however, is that what Miller and Urey created, protein components in water, isn't enough to constitute life. To truly get going, life would have needed three quite special features: a genetic code that would carry the blueprint for making cells; a chemical system – or metabolism – to generate the energy to power the cells; and a sac or membrane to hold it all together. In every organism alive today, the trio is built from the same atoms: carbon, hydrogen, oxygen, nitrogen, phosphorus and sulphur. So, at the most basic level, life's crucible must have offered a ready supply of these atoms and the right conditions for them to come together and form all three of life's essential features.

That turns our attention from the how to the where of life's origins. Researchers studying the origins of life each have their favourite spot. Some sites offer the right molecular ingredients, others provide little, ready-made containers to hold these early reactions. But is it possible that one special place had the perfect combination of all the conditions essential for the chemistry of life? And does a similar place still exist today, on Earth or elsewhere in the universe? The next page summarises some of the main contenders. ∎

DID LIFE COME FROM SPACE?

Panspermia is the idea that life on planets such as Earth could be seeded from space, but how likely is it? "I think it shouldn't be ruled out, but it's not worth considering it until we've more extensively explored likely possibilities on Earth," says John Sutherland at the MRC Laboratory of Molecular Biology in Cambridge, UK.

If life arrived from elsewhere, it would have had to make it through the atmosphere without burning up, then adapt to our planet. A more probable scenario is that some of the building blocks arrived by interstellar transport and were assembled after delivery. Some meteorites contain fatty molecules that can coalesce into membranes, an essential component of all cells. And the building blocks of proteins have been found around comets.

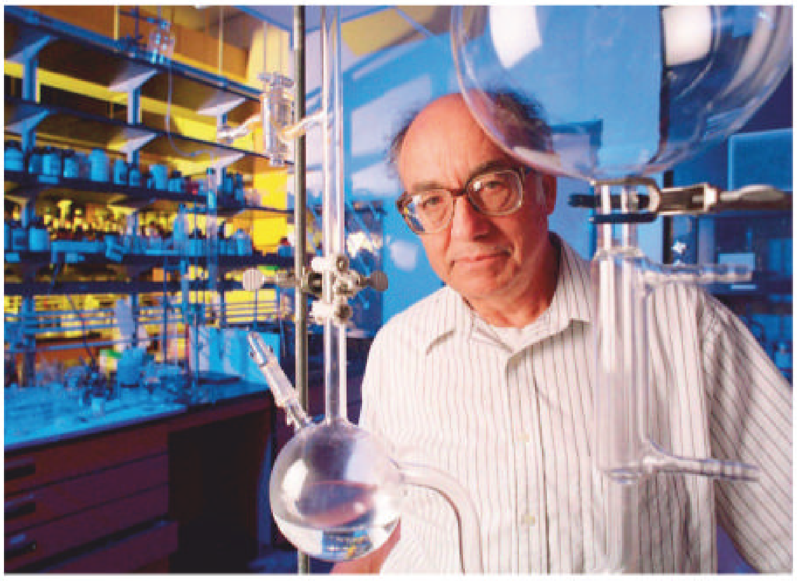
Despite this, there is still some argument over whether these components could have arrived intact in sufficiently large amounts. The chemistry of life may have started independently on our planet and elsewhere in the universe, in which case the quest to pin down its origins at home could help us find it in the great beyond. For every possible cradle of life on Earth, there could be an equivalent in space. The Gale crater on Mars, which is being explored by NASA's Curiosity rover, used to have a lake, and there are signs of alkaline hydrothermal vents on Enceladus and Europa, icy moons of Saturn and Jupiter respectively. And that's just within our own solar system.

UWE MOSER/ISTOCK PHOTO

	TEMPERATURE	WHERE ON EARTH TODAY	ARGUMENTS IN FAVOUR	ARGUMENTS AGAINST
ALKALINE OCEAN VENT Large columns of rock on the sea floor, riddled with tiny pores, where alkaline water bubbles into the ocean	Around 65°C	Lost City in the mid-Atlantic Ocean	Lots of hydrogen; a chemical set-up similar to modern metabolisms; geothermal energy to drive reactions	Too salty for membranes; too wet for large biomolecules
HOT FRESHWATER POOL Small pools on warm volcanic land, repeatedly replenished by geysers or hot springs between dry spells	Around 90°C	Bumpass Hell in California	Wet and dry cycles help large biomolecules form; membranes form naturally if fatty acids are present	Unclear how metabolism could have got started
GEOTHERMAL FIELD Hot, rocky, geothermally active landscapes with cooler water vapour enriched with minerals	Around 150°C	Mutnovsky field in Kamchatka, Russia	Vapour rich in essential elements; water droplets could help RNA to form	Unclear how metabolism could have got started
DESERT Arid land with sporadic rains that bring minerals and compounds from the mountains and atmosphere	Around 80°C	Death Valley, California	Borate from the rocks helps RNA components to form	Unclear how metabolism could have got started
ICE Frozen water riddled with narrow fissures and channels, filled with concentrated brine	Around 0°C	Fresh water at high altitudes or in cold climates	Long strands of genetic material can assemble and build further strands in a nearly self-sustaining system	Unclear how metabolism could have got started
IMPACT CRATER Iron-rich rocks heated by successive meteorite impacts	Around 2000°C* **Upon meteorite impact, then much cooler*	Meteor crater in Arizona	Right conditions for genetic material, proteins and membranes to form	Implies a cyanide-based metabolism, unlike anything on Earth today
TERRESTRIAL HYDROTHERMAL CRATER LAKE A hot lake within a meteorite crater – possibly with ice around the edge	Around 165°C	Lonar crater, India	Conditions are right for three components of early life – genetic material, proteins and membranes	Implies a metabolism unlike anything on Earth today... although if an alkaline vent happened to be nearby then maybe – just maybe – this could have been the place that had it all

PROTEINS, GENES OR CELLS?

A central problem about the origin of life is that living organisms – even the most simple ones – are incredibly complex chemically. Most hypotheses about the first life assume that one or other of its essential components, proteins, genes and cells must have arisen first, with the others coming only later. But which?



REUTERS/ALAMY STOCK PHOTO

Stanley Miller's experiments popularised the "proteins-first" view of life's origins

PROTEINS FIRST

ONE of the earliest ideas about the first step on the road to life was popularised by biochemist Sidney Fox in the wake of the seminal Miller-Urey experiment. He suggested that these amino acids then assembled themselves into simple proteins.

In modern organisms, proteins perform a huge range of functions, including acting as enzymes that speed up essential chemical reactions. From the 1950s onwards, Fox's team produced evidence that protein-like molecules could indeed form from amino acids. These "proteinoids" formed spherical structures that superficially looked like living cells. They could even divide into two, as real cells do, and speed up chemical reactions.

Similar experiments are still being conducted today. Stefan Schiller at the Albert Ludwig University of Freiburg in Germany and his colleagues have made simple proteins just five amino acids long. These chains readily clump together into spherical containers, which the researchers describe as "protocells". The team has also found that the protocells have several life-like properties. They can house large molecules over periods of weeks, just as living cells must play host to DNA and other substances. Furthermore, two protocells can fuse together to form one.

Nevertheless, the proteins-first hypothesis has largely fallen out of favour. Proteins on their own seem to be limited in how life-like they can be. As a result, the idea that proteins came first is a minority view among researchers.

GENES FIRST

A much more popular notion is that life began with a genetic molecule – probably RNA, a close cousin of DNA. In this picture, life began in the "RNA world".

The RNA world hypothesis offers a solution to a baffling conundrum. In all organisms alive today, the hard work is done by proteins. Proteins can twist and fold into a wild diversity of shapes, so they can do just about anything, including acting as enzymes, substances that catalyse a huge range of chemical reactions. But the information to make proteins is stored in DNA molecules. You can't make new proteins without DNA, and you can't make new DNA without proteins. So which came first, proteins or DNA?

In the 1960s, biochemists learned that RNA could fold like a protein, albeit not into such complex structures. This suggested an answer. If RNA could catalyse reactions as well as storing information, some RNA molecules might be capable of making more RNA molecules. And if that was the case, RNA replicators would have had no need for proteins. They could do everything themselves.

It was an appealing idea, but at the time it was complete speculation. No one had shown that RNA could catalyse reactions like protein enzymes. It wasn't until 1982 that chemist Thomas Cech and his team at the University of Colorado discovered an RNA enzyme.

After that, the floodgates opened. Researchers found ever more RNA enzymes in living organisms and created new ones in their labs. RNA wasn't as good at storing information as DNA, being less stable, nor was it as versatile as proteins. But it was a molecular jack of all trades. This suggested that the first life consisted of RNA molecules that catalysed the production of more RNA molecules. Chemist Walter Gilbert at Harvard University coined the phrase "RNA world" in 1986.

For many biologists, the clincher came in 2000, when the structure of cells' protein-making factories (called "ribosomes") was figured out. This work confirmed that, nestling at the heart of these factories, there is an RNA enzyme – and if proteins are made by RNA, surely RNA must have come first.

Still, some issues remain. For one thing, it is unclear whether RNA can replicate itself. Nowadays, DNA and RNA need the help of many proteins to copy themselves. If there ever was a self-replicator, it has long since disappeared. Biochemists have tried and failed to make an RNA molecule that can copy itself unaided.

And there is another huge and obvious problem: where did the RNA come from in the first place? RNA molecules are strings of nucleotides, which, in turn, are made of a sugar with a base and a phosphate attached. In living cells, numerous enzymes are involved in producing nucleotides and joining them together, but of course the primordial planet had no such enzymes.

There are experiments that suggest nucleotides can link up into RNA chains if the conditions are right. It is building the nucleotides that is really hard – because of the shapes of the molecules, it is almost impossible for the sugar to join to a base.

This problem was partially solved in 2009 by John Sutherland at the MRC Laboratory of Molecular Biology in Cambridge, UK. He wondered whether simpler molecules might assemble into a nucleotide without ever becoming sugars or bases. He and his team eventually found a process where they took half a sugar and half a base and stuck them together – forming the crucial sugar-base link that everyone had struggled with. Then, they bolted on the rest of the sugar and the base and stuck on the phosphate last.

In short, the RNA world has amassed a lot of supporting evidence. However, it isn't clear that RNA alone was enough to give rise to life. In recent years, some researchers have suggested that RNA only really reaches its potential when it is paired with proteins – and that both must have existed for life to get started. ›

CELLS FIRST

A third school of thought is that the first organisms were simple blobs, resembling bubbles. They may have been made of long-chain molecules, such as lipids, which formed an outer layer surrounding a watery core. These "protocells" would have resembled modern cells in one key attribute: they acted as containers for all the other components of life. The approach is sometimes called "compartmentalisation first", because it emphasises the need for living organisms to have an outer wall to hold them together.

Researchers have been making such protocells in the lab since the late 1970s, and have demonstrated that hey can behave in startlingly life-like ways – for example, growing when "fed" with more fatty acids.

Jack Szostak at the Howard Hughes Medical Institute in Boston, Massachusetts, has spent years trying to create a protocell similar to what may have preceded the first cells on Earth. He focuses on fatty acids. When dissolved in water, these organic molecules can group together into bubbles, or vesicles, similar to what the first protocells may have looked like. By evaporating the solution that the vesicles float in, Szostak was able to make them grow and divide.

He has also succeeded in combining these fatty acid protocells with RNA. Since 2003, Szostak has been able to persuade protocells to carry a cargo of RNA, and in 2013, with Katarzyna Adamala at the University of Minnesota, he found a way to copy the RNA inside the protocells.

Previously, such copying had the unfortunate side effect of destroying the cell, but Szostak and Adamala discovered that the cell can be stabilised by adding a dash of citrate. The substance is synthesised from citric acid, a chemical found in lemons and oranges. Experiments like these go beyond a strict compartmentalisation-first approach and combine it with the RNA world. ∎

LIFE'S POWER PACK

An alternative way to look for the origin of life comes from the idea that it must have begun with a series of chemical reactions that, through some mechanism, extracted energy from the environment and used it to build life's molecules and structures. But when questions about the first life began to be asked, what powers today's life was itself unclear.

THE biochemist Peter Mitchell cut an eccentric figure. For much of his career in the mid-20th century, he worked in his own lab in a restored manor house in Cornwall, UK, his research funded in part by a herd of dairy cows. His ideas about the most basic process of life – how it gets energy – seemed ridiculous to his fellow biologists.

"I remember thinking to myself that I would bet anything that [it] didn't work that way," biochemist Leslie Orgel wrote of his meeting with Mitchell half a century ago. "Not since [Charles] Darwin and [Alfred Russel] Wallace has biology come up with an idea as counterintuitive as those of, say, Einstein, Heisenberg and Schrödinger." Over the following decades, however, it became clear that Mitchell was right. His vindication was complete when he won a Nobel prize for chemistry in 1978.

Before Mitchell, everyone assumed that cells got their energy using straightforward chemistry. The universal energy currency of life is a molecule called adenosine triphosphate (ATP) – split it, and energy is released. ATP powers most of the energy-demanding processes in cells, from building proteins to making muscles move. In turn, ATP was thought to be generated from food by a series of standard chemical reactions. Mitchell thought otherwise. Life, he argued, is powered not by the kind of chemistry that goes on in a test tube, but by a kind of electricity.

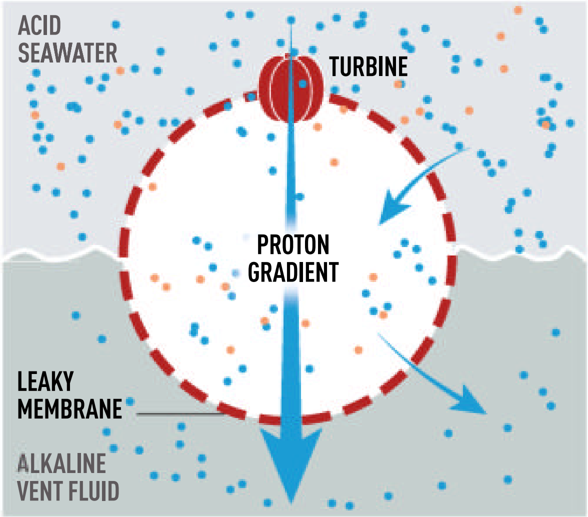
In living cells, the energy from food is used to pump positively charged hydrogen ions, or protons, through a membrane, he said. As protons accumulate on one side, an electrochemical gradient builds up across the membrane. Given the chance, the protons will flow back across, releasing energy that can be harnessed

›

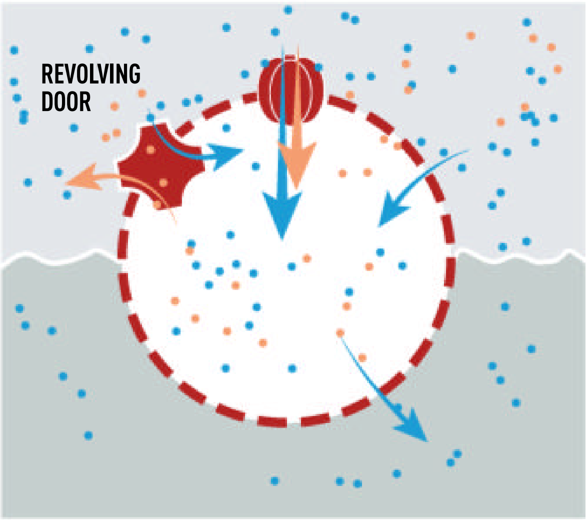
Proton pumps could be how the first living cells on Earth got their energy

● PROTON ● SODIUM ION

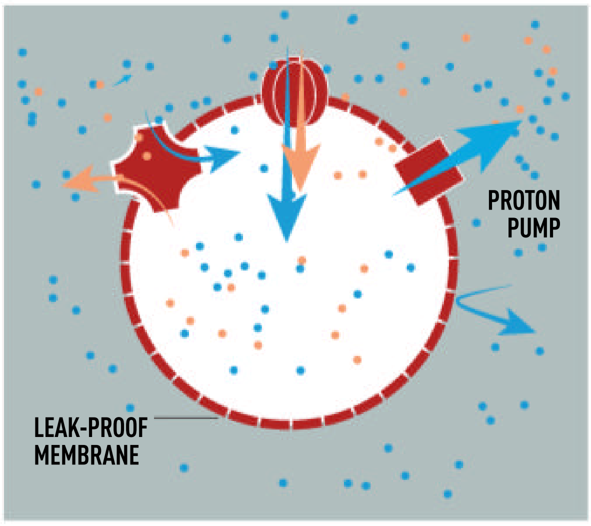
The cell lives on the boundary between acid, proton- rich seawater and alkaline vent fluid. It develops a protein that, like a turbine, extracts energy from the proton gradient (difference in concentration)



Later, cells evolve a "revolving door" protein that effortlessly pumps sodium ions out while letting protons in. The sodium later re-enters through the turbine protein, generating even more energy



Eventually, cells develop a dedicated proton pump and a leak-proof membrane. These cells can generate their own proton gradient across the membrane to obtain energy, and can leave the vent behind



to assemble ATP molecules. In energy terms, the process is analogous to filling a raised tank with buckets of water, then using the water to drive a waterwheel (see diagram, page 13).

Mitchell dubbed his theory chemiosmosis, and it isn't surprising that biologists found it hard to accept. Why would life generate energy in such a complicated and roundabout way, when simple chemical reactions would suffice? It just didn't make sense.

It might be counter-intuitive, but chemiosmosis has turned out to be ubiquitous in the living world. Proton power drives not only cell respiration, but photosynthesis too: energy from the sun is converted into a proton gradient in essentially the same way that other living organisms extract it from food.

This suggests that proton power is no late innovation, but instead evolved early in the history of life, an idea supported by the tree of life. The first branch in the tree is between the two great groups of simple cells, bacteria and archaea. Both of these groups have proton pumps and both generate ATP from proton currents using a similar protein. The obvious explanation is that both inherited this machinery from a common ancestor – the progenitor of all life on Earth.

→
Chapter 2 has more on the evolution of simple cells

Think about the properties of that common ancestor, however, says William Martin at the University of Düsseldorf in Germany, and you come up with a very strange beast indeed. He starts from the assumption that traits found in both the archaea and bacteria are most probably inherited from the common ancestor of all life (though a few have clearly been acquired later by gene exchange), while traits that are distinct presumably evolved independently.

There is no doubt that the common ancestor possessed DNA, RNA and proteins, a universal genetic code, ribosomes (the protein-building factories), ATP and a proton-powered enzyme for making ATP. The detailed mechanisms for reading off DNA and converting genes into proteins were also in place. In short, then, the last common ancestor of all life looks pretty much like a modern cell.

Yet the differences are startling. In particular, the detailed mechanics of DNA replication would have been quite different. It looks as if DNA replication evolved independently in bacteria and archaea, according to Eugene Koonin at the National Center for Biotechnology Information in Bethesda, Maryland.

Beyond that, many biochemical pathways are catalysed by quite different enzymes. The most surprising and significant of these is fermentation, the production of energy from food without oxygen. Fermentation is often assumed to be the primordial method of energy generation. Yet Martin has shown that the enzymes responsible are totally unrelated in archaea and bacteria. It looks as if fermentation evolved twice later on, rather than at the dawn of life.

Even more baffling, says Martin, is that neither the cell membranes nor the cell walls have any details in common. But if that is the case, what sort of a cell was this common ancestor? A cell with no boundary? Impossible! Something unique? If you exclude the impossible, then whatever you are left with must be true.

If Martin is right, the last common ancestor of life on Earth was a sophisticated entity in terms of its genes and proteins, and was powered by proton currents rather than fermentation. Yet at the same time, its bounding membranes were apparently different to anything found today. It was life, but not as we know it. ▮

OUT OF THE HYDROTHERMAL VENT

If proton power is the basic currency of life's energy, the place where life first emerged must be one with plenty of energy to get those proton flows going. This idea suggested what remains one of the most popular hypotheses for where life first emerged.

THE idea about the origin of life known as "metabolism first" – that you must first look for its source of energy – was championed in the late 1980s by Günter Wächtershäuser, a German chemist turned patent lawyer. Wächtershäuser envisioned a series of chemical reactions taking place on crystals of iron pyrite, or fool's gold, in volcanic hydrothermal flows at high pressure and high temperature. This scheme was dubbed the "iron-sulphur world".

However, nowadays, this has been largely supplanted by an idea that originated with Mike Russell, who was then at NASA's Jet Propulsion Laboratory in Pasadena, California. He began exploring the possibility that the first life was powered by currents of electrically charged protons within alkaline vents on the seabed. This geochemical idea is counter-intuitive, and initially didn't go down well with the molecular biologists who dominated the field. But the idea has much to recommend it, and has since attracted many adherents.

Alkaline vents are a very particular kind of hydrothermal vent. In the early 1990s when Russell first hit upon the idea, they were known only from remnants found in ancient rocks. Unlike the black smokers discovered in 1977, formed by the violent reaction of seawater with volcanic lava rising up at the mid-ocean ridges, Russell's vents were much tamer affairs, little more than bubbly rocks riddled with labyrinthine pores.

These vents form when water reacts with the mineral olivine, which is common in the sea floor (and would have been even more common early on, before Earth's crust thickened). The process produces a new mineral, serpentine, and releases hydrogen, alkaline fluids and heat. It also makes the rocks expand and crack, allowing more water to percolate down, sustaining the reaction. The warm, hydrogen-rich effluent ultimately breaks through the sea floor as an alkaline hydrothermal vent.

Interest in alkaline vents rose in 2000, when Deborah Kelley at the University of Washington in Seattle and her colleagues stumbled – if you can stumble in a submersible – across an active alkaline vent field just off the mid-Atlantic ridge, exactly where Russell said such vents should be. The team dubbed it the Lost City partly for its spectacular spires of rock, which form as carbonates precipitate out in the alkaline fluid.

Like ancient vents, the spires of the Lost City are riddled with tiny pores, some with dimensions not dissimilar to that of modern cells. The chemistry fits the bill too: a report in 2008 confirmed the presence of methane and other small hydrocarbons, as well as hydrogen itself.

The vents themselves may be much the same as those around 4 billion years ago, but back then the oceans were very different. The primordial oceans were saturated in carbon dioxide, making them acidic, whereas the seas today are slightly alkaline. There was also practically no oxygen, and without oxygen, iron dissolves readily. The vast banded-iron formations around the world reveal just how much iron was once dissolved in oceans – as oxygen levels slowly rose, › billions of tons of iron precipitated out as rust.

What this means is that the interface between the alkaline vents and the ancient seas would have been much more conducive to primordial biochemistry than today, says Russell. In particular, bubbles of iron-sulphur minerals – which have remarkable catalytic properties – would have formed in the pores. This isn't conjecture: Russell has found ancient vents with a similar structure and even reproduced them in the lab.

The fact that alkaline vents would have had a labyrinth of naturally forming microcompartments is what attracted the attention of William Martin at the University of Düsseldorf in Germany. Such compartments could have been the precursors of biological cell walls that he sought, providing a scaffold within which the stuff of cells could form. Together, Martin and Russell have pointed out that identical iron-sulphur minerals can still be found at the heart of proteins that use hydrogen gas to convert carbon dioxide to sugars (using hydrogen gas) in archaea and bacteria, such as methanogens and acetogens.

→
Chapter 2 has more on the workings of microbes such as archaea and bacteria

The vent fluid would also have contained nitrogen compounds such as ammonia, and conditions would have favoured the production of amino acids, the building blocks of proteins.

That isn't all. In the presence of phosphate, minerals might have catalysed the production of nucleotides – the building blocks of RNA and DNA. And if nucleotides did form by mineral catalysis, the pores in alkaline vents would have had an extraordinary effect.

Simulations by Dieter Braun at the Ludwig Maximilian University in Munich, Germany, and his colleagues show that the temperature gradient between the top and bottom of the pores concentrates nucleotides at one end, which encourages the molecules to join together to form strings of RNA and DNA. These larger molecules would then become concentrated to even higher levels. What's more, the convection currents would produce a continual rise and fall in temperature – as used to make DNA in labs across the world.

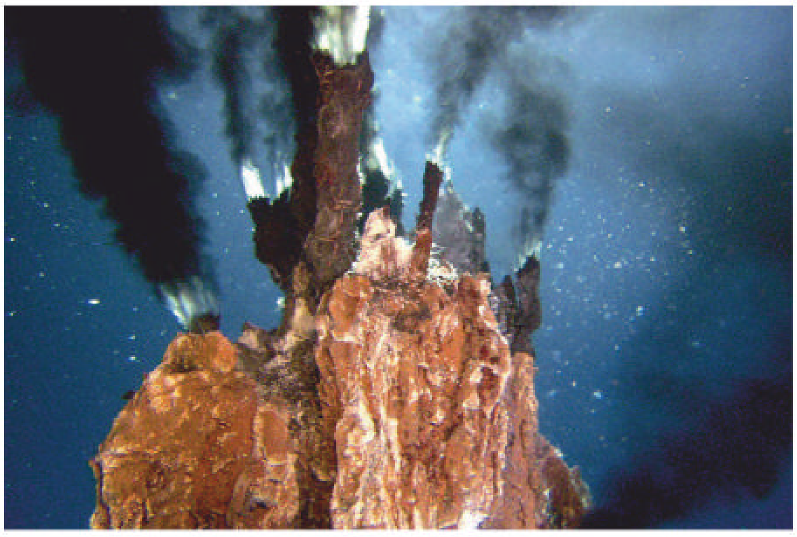
Laboratory experiments have confirmed that these conditions do indeed concentrate nucleotides and nucleic acids. The team also found that fatty acids become concentrated, leading to the spontaneous formation of cell-like bubbles inside the pores.

It is hard to imagine a better setting for the RNA world widely thought to bridge the gap between simple organic chemicals and the complexities of DNA and proteins. So the idea that ancient alkaline hydrothermal vents were the incubators for life looks very plausible even before you consider their most striking feature: a ready-made proton gradient.

↑
Turn back to page 11 for more on the RNA world

Back then, the seas were acidic. Acidity is defined in terms of protons, as acids are rich in them. Russell envisages alkaline fluids bubbling into an acidic ocean, where they would form catalytic mineral "cells" complete with a proton gradient across their inorganic membranes.

Some researchers have dismissed Russell's naturally chemiosmotic "cells" as a mere curiosity, irrelevant to the origin of life. But when Martin and Russell considered the bioenergetics of the simplest prokaryotes, they realised that the first cells could


ALLSTAR PICTURE LIBRARY LTD/ALAMY STOCK PHOTO

An underwater hydrothermal vent captured in the 2005 documentary *Aliens of the Deep*

never have escaped the vents without first mastering chemiosmosis – explaining why Mitchell's bizarre mechanism is so central to life today, and so universal.

For all the astonishing wealth of life on Earth, there are only five ways that carbon dioxide is captured and converted into living matter – and only one of those costs nothing at all. That is the straight reaction of hydrogen with carbon dioxide. This exothermic reaction converts carbon dioxide into simple organic molecules and also releases energy. As exobiologist Everett Shock at Arizona State University in Tempe puts it, it is "a free lunch you're paid to eat". And while hydrogen doesn't usually bubble obligingly out of the ground, it does in alkaline vents.

The reaction of hydrogen with carbon dioxide is central to life in the vents, but there is a big problem: it costs some energy to kick-start the reaction in the first place, while the amount of energy released to fuel growth is paltry. Arguably, it is impossible for such bacteria to grow by chemistry alone. They need the proton power of chemiosmosis.

To understand this, think of the energy stored by ATP as equivalent to £10. If it takes £10 to kick-start a reaction, which then releases £15, a cell has, in theory, gained £5. However, if the only way a cell has to store energy is to make ATP, it can make only one molecule; making two new ATPs would cost £20. So one ATP would have been spent to gain one ATP, and the spare £5 wasted as heat. That isn't consistent with being alive.

For proto-life in the vents, this wouldn't have been an issue. The fluid from the vents would have contained reactive molecules such as methyl sulphide, which would generate acetyl phosphate, a molecule that some bacteria today still use interchangeably with ATP. What's more, the natural proton gradient would have supplemented this energy source by spontaneously generating another primitive form of ATP called pyrophosphate.

Pyrophosphate also acts in much the same way as ATP and is still used alongside ATP by many bacteria and archaea. These bacteria speed up its production using a simple enzyme called pyrophosphatase. Working with Wolfgang Nitschke at the French National Centre for Scientific Research, Russell has shown that this enzyme is found in some of the most primitive cells known, on both sides of the bacteria-archaea divide. It dates right back to the beginning.

So the common ancestor of life could harness the natural proton gradient of ancient vents to produce energy. To escape the vents, just one further step was necessary – reversing the process to store energy.

Chemiosmosis allows cells to save up small amounts of energy – the £5s – that would otherwise be wasted. A reaction can be repeated time and time again, just to pump a proton over a membrane. Like saving up to buy something, eventually the proton gradient will be enough to produce one pyrophosphate or one ATP. The upshot is that proton gradients enable cells to grow and to leave the vents.

Indeed, it appears Mitchell's oddity is a necessary precondition for life. While breaking down sugars can provide enough energy for growth without any need for chemiosmosis, the process – called glycolysis – involves complex pathways and requires lots of sugar, and is thus very unlikely to have been the main source of energy for the first life.

The picture painted by Russell and Martin is striking indeed: the last common ancestor of all life wasn't a free-living cell at all, but a porous rock riddled with bubbly iron-sulphur membranes that catalysed primordial biochemical reactions. Powered by hydrogen and proton gradients, this natural flow reactor filled up with organic chemicals, giving rise to proto-life that eventually broke out as the first living cells – not once but twice, giving rise to bacteria and archaea. ▮

DID EVERYTHING COME FIRST?

We have seen that scientists investigating the beginning of life have speculated that one or another of the components of living organisms predated all the others. But there may be another way to think about the problem: a kind of biological big bang.

THE alkaline vent hypothesis is often described as a metabolism-first scenario, because it emphasises the energetics of life. But this is only part of the picture. In fact, Russell's scenario also includes compartmentalisation from the very beginning – just not in the form of cell membranes.

What if we go further? It has long been thought that the ingredients for life came together slowly, bit by bit, because cells are too complex to have formed all at once. That is why scenarios like protein first and the RNA world have been so prominent. But some researchers argue this entire approach is misguided. It is a bit like trying to build a car by making a chassis and hoping wheels and an engine will spontaneously appear. Instead, recent experiments suggest that all the ingredients for life could have formed together in a chemical big bang.

Two lines of evidence are converging to suggest this. It turns out that all the key molecules of life can form from the same simple carbon-based chemistry. What's more, they easily combine to make startlingly life-like "protocells".

Life can be boiled down to three core systems. First, it has structural integrity – that means each cell has an outer membrane holding it together. Second, life has metabolism, a set of chemical reactions that obtain energy from its surroundings. Finally, life can reproduce using genes, which contain instructions for building cells and are passed on to offspring.

Biochemists know the chemicals underpinning these processes too. Cell membranes are made of lipids, molecules containing long chains of carbon

Organic molecules in the Murchison meteorite could hold clues to the origin of life

MATTEO CHINELLATO/ALAMY STOCK PHOTO

atoms. Metabolism is run by proteins – chains of amino acids, twisted into pretzel shapes – especially enzymes, which help catalyse chemical reactions, speeding them up. And genes are encoded in molecules called nucleic acids, such as deoxyribonucleic acid, better known as DNA.

Beyond this, things start to become more complicated. Life's three core processes are intertwined. Genes carry instructions for making proteins, which means proteins only exist because of genes. But proteins are also essential for maintaining and copying genes, so genes only exist because of proteins. And proteins – made by genes – are crucial for constructing the lipids for membranes. Any hypothesis explaining life's origin must take account of this. Yet, if we suppose that genes, metabolism and membranes were unlikely to have arisen simultaneously, that means one of them must have come first and "invented" the others.

Hypotheses like the RNA world work along these lines, but as we have seen, they tend to fall short of producing living systems in the lab. So researchers like David Deamer at the University of California, Santa Cruz, have begun exploring the seemingly less plausible alternative that all three systems emerged together in a highly simplified form.

This isn't a new idea. In 1971, Hungarian biochemist Tibor Gánti wrote a book in which he imagined the simplest object that biologists would consider alive. His"chemoton" consisted of a crude metabolism, based on enzymes, which made genes and a membrane. When the genes copied themselves, they released by-products that ended up in the membrane, causing the chemoton to grow and ultimately divide. Gánti's ideas failed to get recognition until the early 2000s, however, by which time others had independently hit on something similar. Now, the everything-first hypothesis is gaining momentum.

The first line of support for it comes from the biochemistry of life's three key systems. Nucleic acids such as RNA are chemically very different from proteins, which differ again from lipids. So, until recently, biochemists had assumed that these three components of life were unlikely to form in the same place from the same starter chemicals. That assumption seems to be wrong.

An early clue came from meteorites, many of which are as old as Earth, and therefore tell us what the planet was like when it was new. One of the most studied is the Murchison meteorite, which hit Australia in 1969. In 1985, Deamer found lipid-like molecules in it, which could form membranes. Others have found amino acids and, in 2008, Zita Martins, then at Imperial College London, identified a component of RNA in the Murchison meteorite. None of these chemicals were plentiful, but their presence indicated they could form together.

Meanwhile, Ernesto Di Mauro at Sapienza University of Rome in Italy has spent two decades exploring how this might happen on Earth. He focuses on formamide, a chemical related to cyanide, with just six atoms in each molecule. It is found throughout the universe and was probably common on the newly formed ›

“All cellular subsystems could have arisen simultaneously through common chemistry”

planet. In 2001, his team found that formamide could give rise to several components of RNA if it was heated to 160°C in the presence of minerals like limestone. The researchers later discovered that a common type of clay called montmorillonite helps. Formamide can also generate amino acids, the building blocks of proteins.

And formamide isn’t the only chemical capable of such feats. By combining a similar organic compound called cyanamide with other simple chemicals, John Sutherland at the MRC Laboratory of Molecular Biology in Cambridge, UK, has created nucleotides, the building blocks of RNA. The reaction requires ultraviolet light, heating, drying and wetting with water. Sutherland’s team found that the same starting chemicals can also make the precursors of amino acids and lipids. “All the cellular subsystems could have arisen simultaneously through common chemistry,” he concluded. The key is what Sutherland calls “Goldilocks chemistry”: a mixture with enough variety for complex reactions to occur, but not so much that it becomes a jumbled mess.

So there are ways in which the key molecules of life might all have been created together. But how did they then combine into a crude cell? Deamer argues that the first lipids spontaneously formed membrane-based protocells, but he also thinks the three groups of molecules work together closely. Lipid containers help RNA and proteins to form and RNA to replicate, and RNA stabilises the lipid membranes. If all are present, the system works better, he says.

The Nobel-prizewinning biochemist Jack Szostak has taken remarkable strides toward revealing how this might have happened. Starting in 2003, his team built model cells with outer layers of fatty acids surrounding an internal space that could host RNA. These protocells formed particularly quickly in the presence of tiny particles of montmorillonite, which often became trapped inside them, carrying RNA inside too.

The one system still missing from these protocells is metabolism. This is particularly challenging because it means creating entire sequences of chemical reactions. In modern organisms, these are controlled by battalions of protein enzymes, which can’t have existed when life began. However, other researchers have begun finding ways to get metabolic chemical reactions going without proteins. It turns out that many of the key reactions can be driven by metals like iron, often paired with sulphur, which have always been abundant on Earth. Szostak and others have recently shown that clusters of iron and sulphur atoms can form within protocells, driven by ultraviolet light. It remains to be seen whether metabolic reactions can work in the protocells.

Nevertheless, Szostak’s protocells are a promising model for what the first living organisms might have looked like. Despite containing just a handful of chemicals, they grow and reproduce and carry RNA “genes” that can copy themselves. It is too early to say whether they arose from the sorts of chemistry advocated by Di Mauro or whether Sutherland is closer to the mark. That depends on the setting in which life emerged, which we can never know for certain. Intriguingly, though, the chemistry itself helps us narrow down the options. ■

NewScientist
ESSENTIAL GUIDES

New Scientist
ESSENTIAL GUIDE №10
BASICS OF RELATIVITY
THE BIG BANG UNIVERSE
DARK MATTER AND DARK ENERGY
BLACK HOLES
GRAVITATIONAL WAVES
THE HUNT FOR QUANTUM GRAVITY
AND MORE
EINSTEIN'S UNIVERSE
RELATIVITY AND THE COSMOS IT BUILT
EDITED BY
RICHARD WEBB
New Scientist
ESSENTIAL GUIDE №11
HOW LIFE BEGAN
THE WORLD OF MICROBES
ORIGINS OF COMPLEX LIFE
ANIMALS, PLANTS AND FUNGI
EARTH'S MASS EXTINCTIONS
BIODIVERSITY UNDER THREAT
AND MORE
LIFE ON EARTH
THE STORY OF OUR UNIQUE LIVING PLANET
EDITED BY
MICHAEL MARSHALL
NEW SCIENTIST ESSENTIAL GUIDE LIFE ON EARTH
NEW SCIENTIST ESSENTIAL GUIDE EINSTEIN'S UNIVERSE
NEW SCIENTIST ESSENTIAL GUIDE NUTRITION & DIET
NEW SCIENTIST ESSENTIAL GUIDE CLIMATE CHANGE
NEW SCIENTIST ESSENTIAL GUIDE THE HUMAN BRAIN

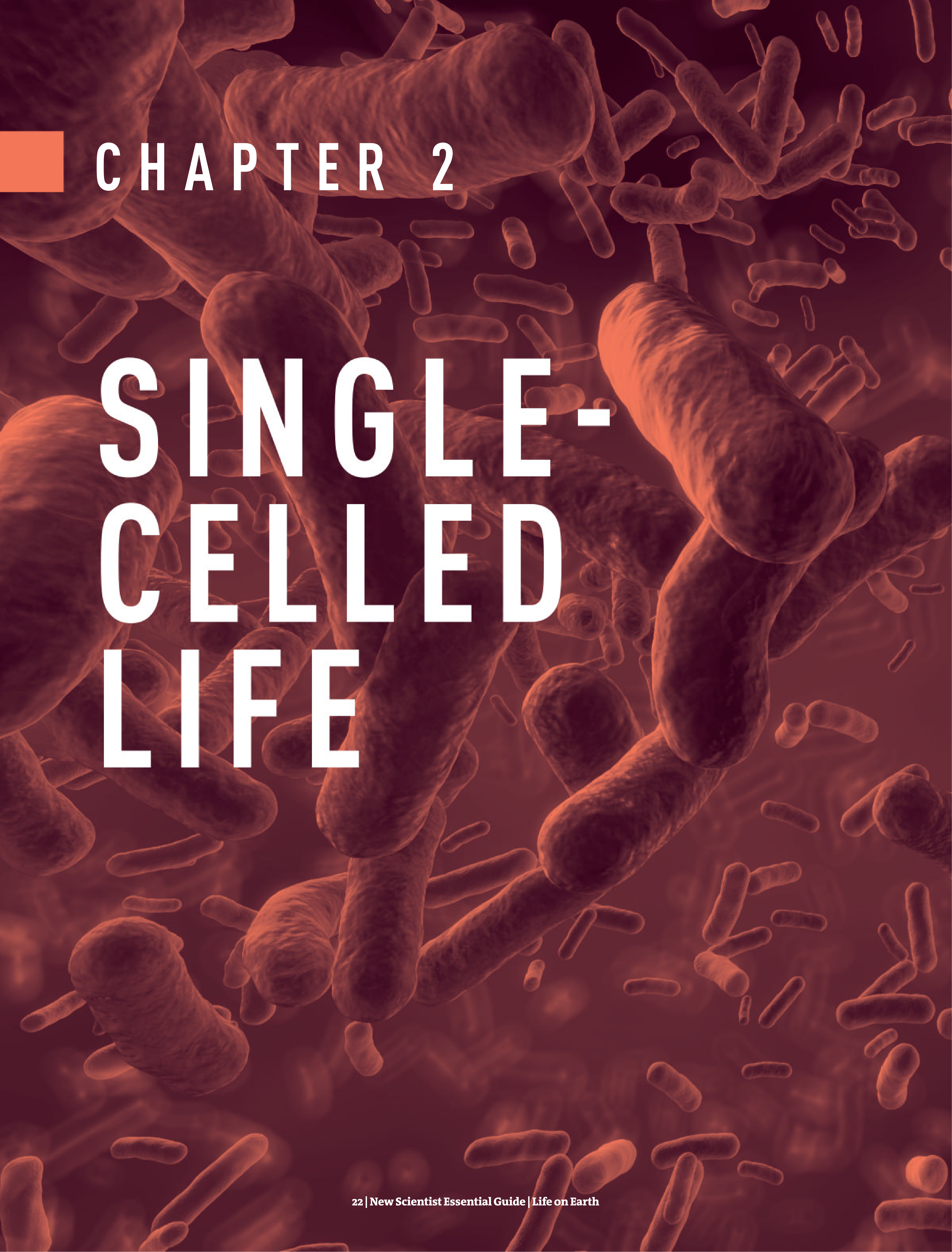
NEW SCIENTIST ESSENTIAL GUIDES
DELIVERED DIRECT TO YOUR DOOR

Based on the best coverage from *New Scientist*, the *Essential Guides* are comprehensive, need-to-know compendiums covering the most exciting themes in science and technology today.

Get the series, including the recently published issue on Einstein's universe, with an *Essential Guides* subscription. It means you don't have to search for issues in the shops – we can deliver them direct to your door.

FOR MORE INFORMATION ON FUTURE ISSUES AND SUBSCRIPTION OFFERS, VISIT:

NEWSCIENTIST.COM/ESSENTIALGUIDE



CHAPTER 2

SINGLE-CELLED LIFE

Most life on Earth is microscopic and single-celled. The origins of these life forms probably lie in Earth's first billion years. For most of our planet's history, they were all that existed.

But in developing tricks such as photosynthesis to extract energy from their environment, they fundamentally changed the planet and created the conditions for more complex life forms to evolve.

Even now, they have a diversity and a range of lifestyles that puts us lumbering multicellular lumps to shame, and that sets the tone for life on Earth today.

ON THE ORIGIN OF MICROBES

When the first single-celled life forms evolved on Earth is a matter of intense controversy. It was early, that much is clear. Since then, members of the two great microbial "domains" – the bacteria and the archaea – have been busy evolving Earth, too.

JOHN ARCHER/ISTOCK PHOTO
PREVIOUS PAGE: SPANTELDOTRU/ISTOCK

THE oldest confirmed fossil organisms are single-celled microorganisms. They were found in 3.5 billion-year-old rocks in an extinct volcano in the Dresser Formation in the hot, dry, remote Pilbara region of Western Australia.

The fossils include stromatolites – layered rock structures created by microorganisms – and circular holes left in the rock by gas bubbles that look like they were once trapped by sticky microbial substances. Both types of structures are preserved in geyserite, a type of rock that is only found in and around freshwater hot springs in volcanic areas on land.

In a 2019 study, Raphael Baumgartner at the University of New South Wales in Australia and his colleagues drilled into the rocks to get the best-preserved samples. They found many layers that looked like stromatolites. These contained preserved organic matter, including strands of the sort seen when microbes form slimy layers called biofilms. Multiple chemical analyses indicate that the organic matter came from living organisms.

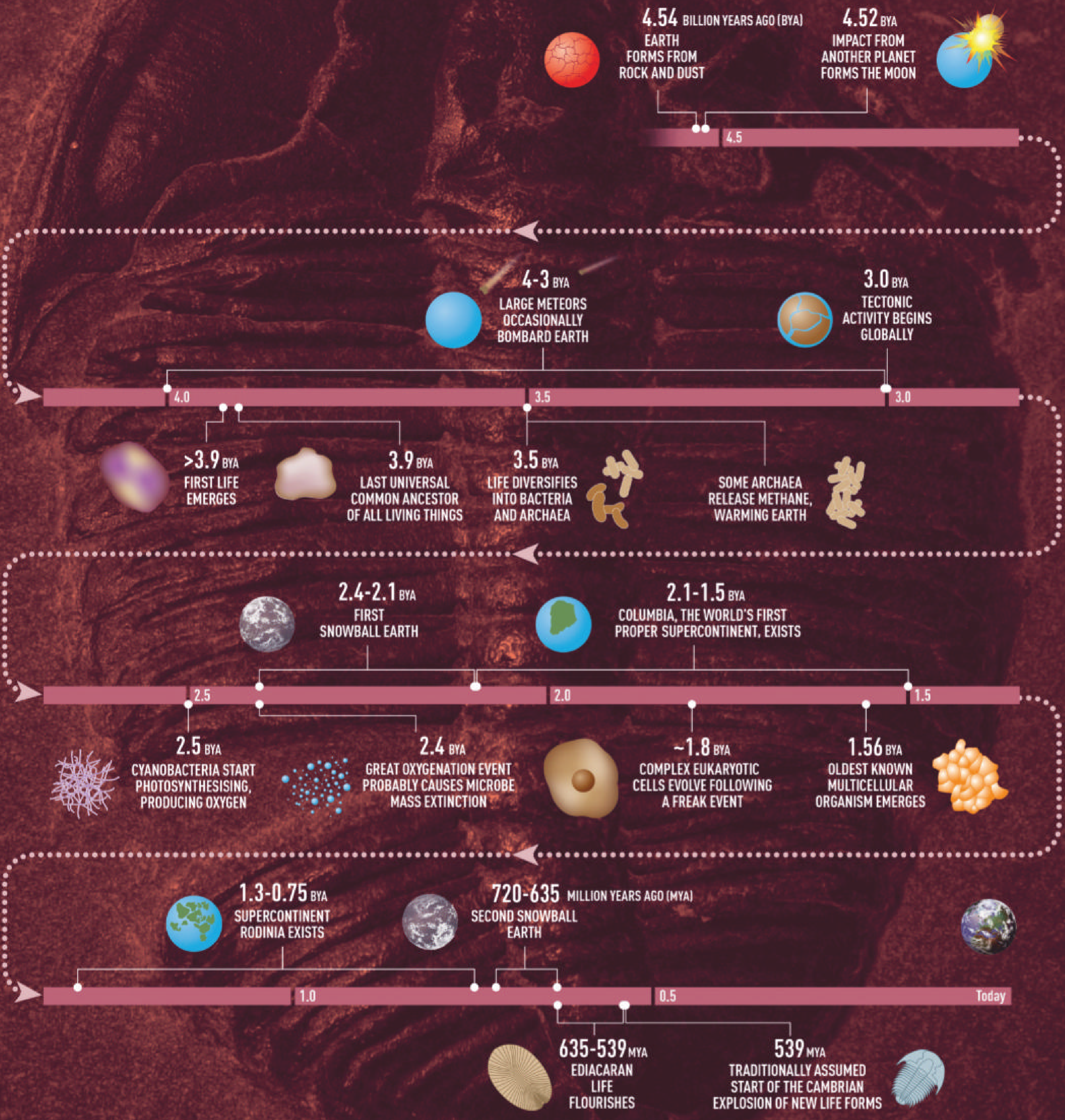
It isn't clear how much earlier life existed. The Pilbara cells have complex membrane structures and link together into chains, which suggests they were already a complex ecosystem. Earth itself formed some 4.54 billion years ago, so there is a gap of about 1 billion years in which life could have started.

Claims of older fossils are regularly touted, and the

›

A TIMELINE OF LIFE

The evolution of the first microbes perhaps as much as 3.9 billion years ago means Earth has harboured life for almost all of its history – but for most of that time only in simple forms



4.54 BILLION YEARS AGO (BYA)
EARTH FORMS FROM ROCK AND DUST

4.52 BYA
IMPACT FROM ANOTHER PLANET FORMS THE MOON

4-3 BYA
LARGE METEORS OCCASIONALLY BOMBARD EARTH

>3.9 BYA
FIRST LIFE EMERGES

3.9 BYA
LAST UNIVERSAL COMMON ANCESTOR OF ALL LIVING THINGS

3.5 BYA
LIFE DIVERSIFIES INTO BACTERIA AND ARCHAEA

SOME ARCHAEA RELEASE METHANE, WARMING EARTH

3.0 BYA
TECTONIC ACTIVITY BEGINS GLOBALLY

2.5 BYA
CYANOBACTERIA START PHOTOSYNTHESISING, PRODUCING OXYGEN

2.4-2.1 BYA
FIRST SNOWBALL EARTH

2.4 BYA
GREAT OXYGENATION EVENT PROBABLY CAUSES MICROBE MASS EXTINCTION

2.1-1.5 BYA
COLUMBIA, THE WORLD'S FIRST PROPER SUPERCONTINENT, EXISTS

~1.8 BYA
COMPLEX EUKARYOTIC CELLS EVOLVE FOLLOWING A FREAK EVENT

1.56 BYA
OLDEST KNOWN MULTICELLULAR ORGANISM EMERGES

1.3-0.75 BYA
SUPERCONTINENT RODINIA EXISTS

720-635 MILLION YEARS AGO (MYA)
SECOND SNOWBALL EARTH

635-539 MYA
EDIACARAN LIFE FLOURISHES

539 MYA
TRADITIONALLY ASSUMED START OF THE CAMBRIAN EXPLOSION OF NEW LIFE FORMS

> **“Microorganisms are so diverse that they can thrive in the most implausible places”**

earliest known chemical traces of life appear to date from 4.1 billion years ago. But this evidence is controversial, partly because Earth is thought to have been battered by meteorites between 4 billion and 3.8 billion years ago, rendering it uninhabitable. However, in recent years, this Late Heavy Bombardment has been reassessed. Simulations have suggested that, rather than happening in one short, sustained blast, large meteorites kept hitting at a low rate until about 3 billion years ago. These impacts would have caused problems for life, but couldn’t have obliterated it.

That helps explain why there was little pushback in 2018 when a new calculation put the origins of life firmly before 3.8 billion years ago. Davide Pisani at the University of Bristol, UK, and his colleagues compiled genetic data from 102 living species and built a family tree showing how they were related. Then they took some firm dates from the fossil record and used these to work out how fast evolution has been happening, allowing them to estimate when some of the key stages in the history of life occurred.

One of these was the origin of the last universal common ancestor (LUCA), which they calculated lived at least 3.9 billion years ago. The very first organisms would have arisen even earlier.

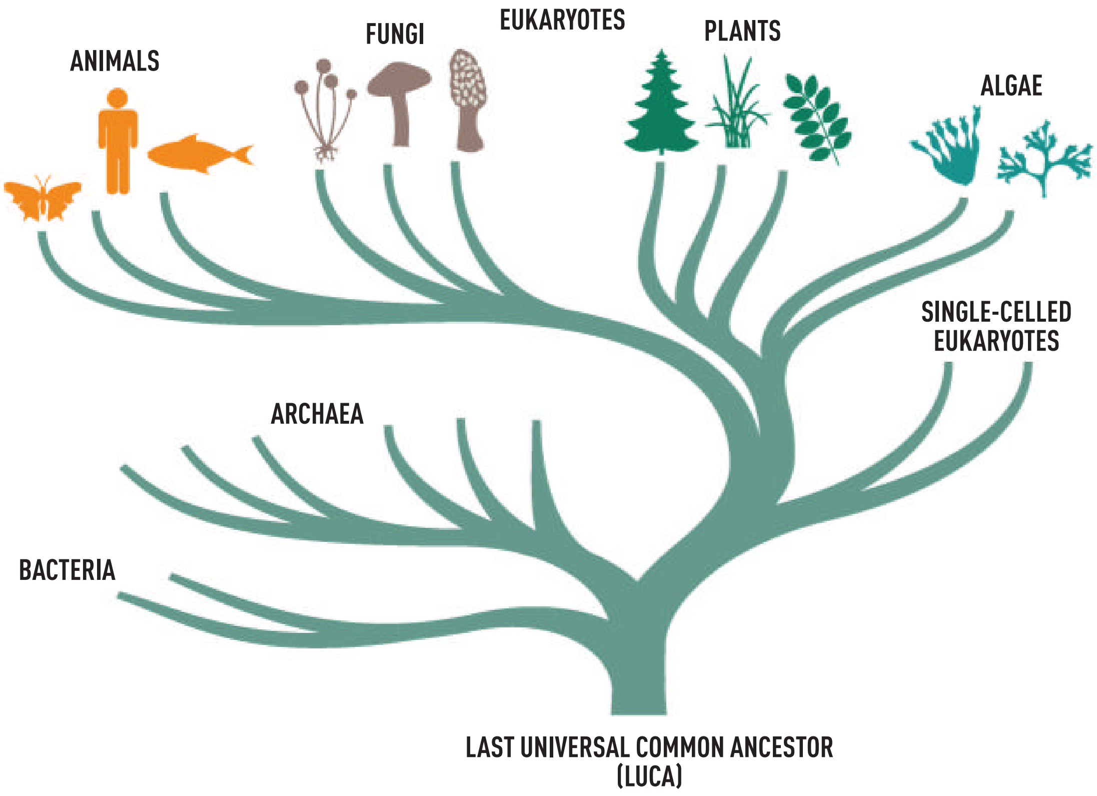
We already have some idea of what LUCA was like. Several teams have used genetic methods similar to Pisani’s to figure out which genes it had and which evolved later. The most comprehensive was published in 2016 by William Martin at the University of Düsseldorf, Germany, and his colleagues. They identified 355 genes that LUCA probably possessed. These indicate that it lived somewhere hot and used carbon dioxide to make acetate, which served as its food. Yet it didn’t possess the mechanisms for making amino acids – the building blocks of proteins – so probably acquired them from the environment. LUCA, it seems, was a complex organism, but still missing some key abilities.

Over the next billion years, life diversified. According to Pisani’s study, the first big split took place at least 3.4 billion years ago. It resulted in two groups of microorganisms, bacteria and archaea. Each is a domain, the largest categories into which living organisms are grouped. (The other domain, the complex-celled eukaryotes, encompasses plants, animals and fungi.)

→
Chapter 3 is all about eukaryotic life

Bacteria have been known for more than a century. In contrast, archaea were long thought to be just another kind of bacteria. The two look almost indistinguishable under the microscope. It took until the late 1970s for them to be recognised as distinct, based on their DNA. Further studies have shown that they also have distinct biochemistry. In particular, many archaea have evolved to live under extreme conditions, such as high temperatures.

In general, microorganisms show a diversity of ways of gaining energy from their environment that means they can thrive in the most implausible places. While



The last universal common ancestor, or LUCA, is the name given to the organism that gave rise to all domains of life known to exist

humans nourish ourselves by eating food such as plants and fish, microorganisms often do so in ways that are quite unlike ours.

In 1977, the discovery of giant gutless worms thriving in vast numbers around hydrothermal vents stunned scientists. What did they feed on, where no light can penetrate and little food sinks down from above? It was Colleen Cavanaugh, now at Harvard University, who proposed that they get their energy from the hydrogen sulphide produced by the vents, with the help of chemosynthetic bacteria housed in special organs. In the absence of light, the bacteria use hydrogen sulphide in a reaction to produce dark carbon. By 1983, Cavanaugh had shown that vent worms do indeed feed on this dark carbon. In the same year, similarly rich oases of life were discovered around methane seeps on the sea floor, again thanks to chemosynthetic bacteria.

←
Turn back to page 15 for more on the chemistry of hydrothermal vents

Many single-celled organisms sustain themselves by chemosynthesis: they obtain energy from simple chemicals found in their surroundings. There are many forms of chemosynthesis. For instance, some archaea nourish themselves using a method called methanogenesis. So-called methanogens harness either carbon dioxide or acetic acid to obtain energy, releasing methane as a waste.

It looks like their evolution played a key role in the history of life on Earth. Greg Fournier and Jo Wolfe at the Massachusetts Institute of Technology have estimated that methanogenesis originated in some archaea a whopping 3.5 billion years ago, or perhaps even more. Support for this surprisingly early date comes from chemicals in rocks that indicate there was methane in the air by then.

That fits with some global changes that were happening too. Atmospheric models have suggested Earth had liquid water at that time, yet the sun wasn't as bright as it is now and couldn't have been melting ice. But methane, a powerful greenhouse gas, would have lent a hand. Archaea, it seems, were the first organisms to affect Earth's climate. By keeping the planet warm, they propped up the rest of the primordial ecosystem too.

Methanogenesis was revolutionary, but it is an inefficient form of nutrition. Research published in 2018 revealed how life evolved progressively better ways to feed itself. First, it relied on chemical reactions that yielded little energy, including methanogenesis. Later, some archaea evolved the ability to use sulphur, which is a better source of energy. Then, others began to use something even more effective: oxygen. But that was only possible once there was oxygen in the air.

For the first 2 billion years of Earth's history, there was no free oxygen. Instead, it was locked up in minerals and other chemicals because it readily reacts with different elements. All that changed 2.4 billion years ago with the Great Oxidation Event – and microorganisms played a key part in that happening, too. ▮

THE FIRST PHOTOSYNTHESISERS

Today, the air on planet Earth is rich in oxygen, which animals like us need to power our own metabolisms. But it wasn't always so. Oxygen only accumulated because some microorganisms learned to harness the power of sunlight – perhaps the single most important development in the history of life.

WHEN oxygen first started accumulating in the air 2.4 billion years ago, it plunged the planet into crisis. The stench of death was everywhere as whole branches of the tree of life were pruned almost to oblivion – all because of the waste gas pumped into the atmosphere by one incredibly successful species.

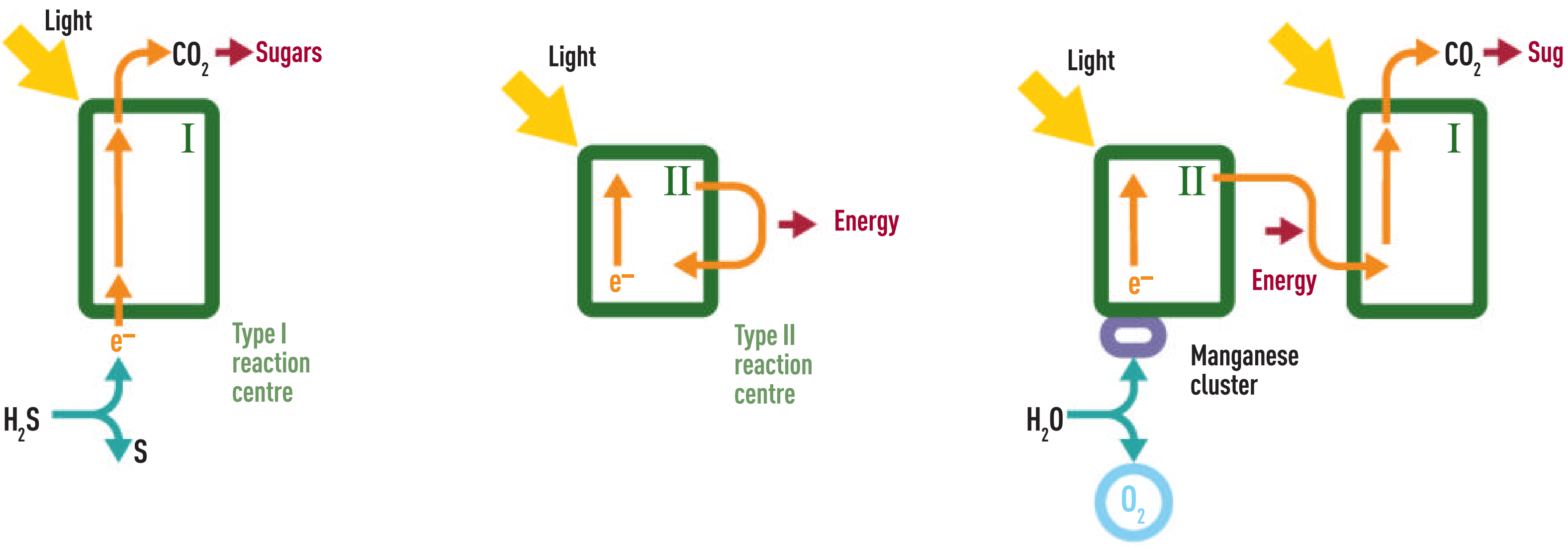
This was arguably the most tumultuous episode in life's history. Life had been thriving for well over a billion years when a new kind of cell appeared on the scene, one that harvested the sun's energy using a process that generates a highly toxic by-product – oxygen. These cells were soon growing in such unimaginable numbers in the primordial oceans that they transformed Earth's atmosphere.

At the time, this was a catastrophe. The rise of oxygen may have wiped out a greater proportion of life than in any other mass extinction. But the very property that makes oxygen so dangerous, its high reactivity, also makes it a rich source of energy. Life soon started to exploit this – including, of course, our animal ancestors.

In recent decades, our view of this crucial episode has been turned upside down. The textbooks will tell you that oxygen levels began climbing soon after

There are several forms of photosynthesis, but only one makes oxygen as a by-product

	TAKE ELECTRONS FROM HYDROGEN SULPHIDE (H_2S)	RECYCLE ELECTRONS	TAKE ELECTRONS FROM WATER
Done by:	Green sulphur bacteria	Purple bacteria	Plants, algae, cyanobacteria
Advantage:	H_2S is easy to split	No electron source required	Unlimited supply of water
Disadvantage:	Supply of H_2S is limited	Provides energy only. Other reactions needed to turn CO_2 into food	Water is hard to split



photosynthesis evolved, but we now know that some cells started photosynthesising as long as 3.4 billion years ago, long before oxygen levels began to rise.

At its heart, photosynthesis is about harvesting the sun's energy. Plants use this energy to make food by building chains of carbon from carbon dioxide. The process produces sugars that can be used as an energy source or to make more complex molecules, from proteins to DNA. But contrary to what you might expect, it doesn't necessarily produce oxygen. In fact, many bacteria turn light and CO_2 into food without producing oxygen. What's more, recent discoveries suggest they have been doing so for nearly as long as there has been life on Earth.

In 2004, Michael Tice and Donald Lowe, both then at Stanford University in California, were studying rocks in South Africa that formed in shallow water 3.41 billion years ago. They found fossil structures rather like the microbial mats formed by photosynthetic bacteria today, but no sign that any oxygen was produced. The most likely explanation, they think, is that these cells were carrying out anoxygenic photosynthesis.

Since that discovery, we have come face to face with some of these early photosynthetic microbes. In 2011, Martin Brasier at the University of Oxford and his colleagues discovered fossils of individual bacterial cells in rocks that formed 3.43 billion years ago, in what is now western Australia. They lived in a well-lit setting, possibly an intertidal zone. The chemical make-up of the rocks, along with the plentiful light, strongly suggests that some of the cells photosynthesised without producing oxygen.

It may seem surprising that anoxygenic photosynthesis evolved so soon after life itself – the earliest fossils we know of are only slightly more ancient. But Nick Lane at University College London, who studies life's origins, thinks that once cells capable of living on chemical energy had evolved, it wasn't a huge step for them to start exploiting light energy instead. Both ultimately come down to the flow of electrons.

For researchers like Lane, the mystery is instead why it took so long for the oxygen-producing form of photosynthesis to evolve. It may not have emerged until around 2.4 billion years ago, perhaps a billion years after anoxygenic photosynthesis appeared. Given the advantages of oxygen-producing photosynthesis, why the delay?

Photosynthesis has two main steps. In the second, electrons are added to CO_2 to help convert the molecule into sugars. But the first step is getting the electrons. They are stripped from a source molecule and used to generate an electrochemical gradient that powers the second step.

In oxygenic photosynthesis, the source molecule is water. Removing electrons splits water molecules into hydrogen ions and oxygen gas. The hydrogen ions and electrons play a key role in turning CO_2 into sugars.

The oxygen, though, is an unneeded by-product.

In anoxygenic photosynthesis, different molecules provide the electrons. One of the most common donors is hydrogen sulphide. Splitting it generates sulphur as a waste product instead of oxygen. The advantage of hydrogen sulphide is that it is very easy to remove electrons from, or oxidise. It was also common in the early ocean, but probably got used up quickly in surface waters where anoxygenic photosynthesis took place.

The great advantage of using water as the electron donor instead is that there is a pretty much endless supply of it in the oceans. The drawback is that water is difficult to oxidise. We are still struggling to do it: researchers have been trying for decades to develop cheap, energy-efficient ways of splitting water to produce hydrogen gas for fuel.

So it makes sense that photosynthesising bacteria first exploited easy-to-oxidise molecules before switching to water. The conventional view, supported by Robert Blankenship at Washington University in St Louis, Missouri, and many other researchers, is that oxygenic photosynthesis gradually evolved from the anoxygenic version through a series of intermediate steps. But over two decades, John Allen, working at Queen Mary, University of London, devised an alternative scenario that is almost deliberately implausible. He argues that it happened by accident, and only that can explain the billion-year delay.

Any scenario for how oxygenic photosynthesis got started has to deal with four significant facts.

Fact one: there are two related, but distinct, types of anoxygenic photosynthesis. Some bacteria have what is called a type I reaction centre, which takes electrons from sources like hydrogen sulphide and sends them down a one-way street: each electron is used just once. Other bacteria carry a type II reaction centre that recycles electrons internally, making them less dependent on an external electron source (see diagram).

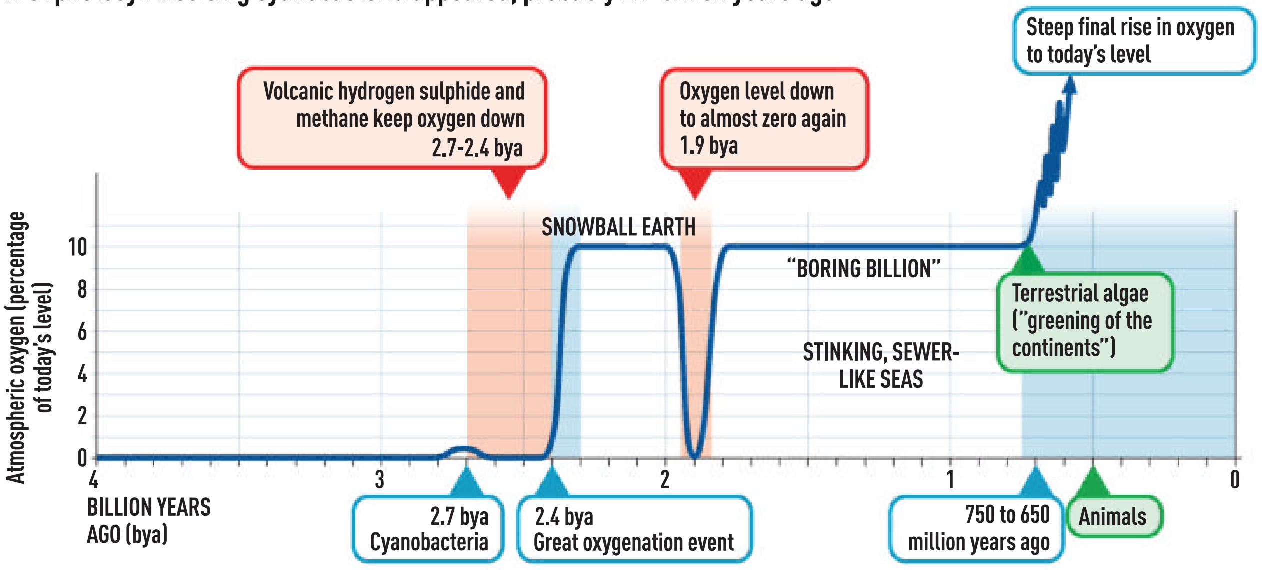
Fact two: oxygenic photosynthesis involves a type I and a type II reaction centre working in tandem. Fact three: even though cyanobacteria have both reaction centres, it is only the type II centre that splits water and generates oxygen, at a site that contains four manganese atoms arranged around a calcium atom. Finally, fact four: anoxygenic photosynthetic bacteria that have a type II reaction centre lack this cluster of manganese and calcium.

Blankenship thinks it is the final two facts that are most important and point towards a simple scenario. The type I centre evolved first, he thinks. Then, the genes encoding its machinery were acquired by another group of bacteria – gene-swapping was and is rife among bacteria. In this group, the machinery gradually became modified, forming the first type II reaction centre. Later, the descendants of these bacteria began to incorporate metal atoms into it. Eventually, they arrived at a configuration that included four atoms of manganese and one of calcium. They could now oxidise water and perform oxygen-generating photosynthesis using just a type II reaction centre.

Only later did this group's descendants acquire the type I machinery via gene transfer, giving rise to cyanobacteria, claims Blankenship. So he thinks it is just a coincidence that cyanobacteria have two different reaction centres.

This scenario makes one clear prediction – there

The rise of oxygen in Earth's atmosphere has experienced many setbacks since the first photosynthesising cyanobacteria appeared, probably 2.7 billion years ago



were once bacteria that generated oxygen through photosynthesis, but were distinct from cyanobacteria. They would have been the missing link between the anoxygenic bacteria with a type II reaction centre – including what are called purple bacteria, and are still alive today – and the oxygen-generating cyanobacteria,. Let's call them "indigo" bacteria. No indigo bacteria have ever been found, though – instead, Blankenship and others have tried to show that they could have existed.

Perhaps most significantly, a team at Arizona State University in Tempe has tried to turn a purple bacterium into something like an indigo bacterium. The researchers modified the purple one so it could bind a manganese ion to its reaction centre and use it to react with molecules containing oxygen. It isn't oxygenic photosynthesis, but it is a step towards it.

Even if biologists do one day engineer an indigo bacterium in the lab, though, this wouldn't prove they could evolve naturally. And to Allen, the gradual evolution scenario can't explain all the facts. Why would such an apparently simple sequence of events have taken up to a billion years to occur? Why did oxygenic photosynthesis evolve only once, in cyanobacteria, as far as we know? And why do all cyanobacteria have both kinds of reaction centres?

Allen also thinks the type I centre evolved first, but from there, his scenario is very different. He thinks that, early in their history, these bacteria experienced some kind of genetic glitch that duplicated the entire set of genes for making a type I reaction centre. The spare copy was free to take on a different role, and it evolved the ability to recycle electrons – the first type II reaction centre. Having two distinct reaction centres allowed these "proto-cyanobacteria" to thrive in a wide range of environments, Allen proposes. When there was plenty of hydrogen sulphide, they used their type I reaction centre. When hydrogen sulphide ran low, the bacteria switched to using their type II reaction centre, recycling the electrons they had gathered.

Then one day, disaster struck: some proto-cyanobacteria drifted into a shallow marine environment that was rich in manganese but poor in hydrogen sulphide. The bacteria duly switched to a type II reaction. But when ultraviolet light hits manganese, it strips off electrons, so there were actually plenty available – and these electrons quickly clogged the cyclic type II reaction centre. The resulting manganese ions would have reacted with water to form manganese oxide, but there was plenty more manganese around, producing more than enough electrons to kill the microbes.

Well, almost all of them. One lucky proto-cyanobacterium survived, Allen suggests, because a mutation wrecked the switch that turned on only one kind of reaction centre at any time. With both kinds in action together, electrons from the manganese could flow through the type II centre before being siphoned off by the type I centre, preventing a blockage. In other words, the two reaction centres would have been working together, just as they do in cyanobacteria today.

But how did the descendants of this bacterium go from getting electrons from manganese to getting them from water? Well, in a way, they didn't. To this day, manganese provides the electrons needed for photosynthesis in all plants. However, the electrons now come from a cluster of manganese atoms within the type II reaction centre, and this cluster has a

›

remarkable ability – after it has given up electrons, it steals others from water molecules, splitting them apart and liberating oxygen.

Once early cyanobacteria had evolved this kind of type II centre, they needed only trace amounts of manganese. They could then spread from manganese-rich environments and start exploiting the abundant CO_2 available at the time, with the help of an unlimited supply of water and sunshine. Soon, immense numbers of cyanobacteria were spewing out enough oxygen to transform the atmosphere.

If Allen's hypothesis is correct, proto-cyanobacteria had to stumble into a highly unusual manganese-rich environment and lose control of a key genetic switch at the same time. Allen agrees this is improbable, but this could be why oxygenic photosynthesis took a billion years to appear. A bacterium had to have two accidents at once.

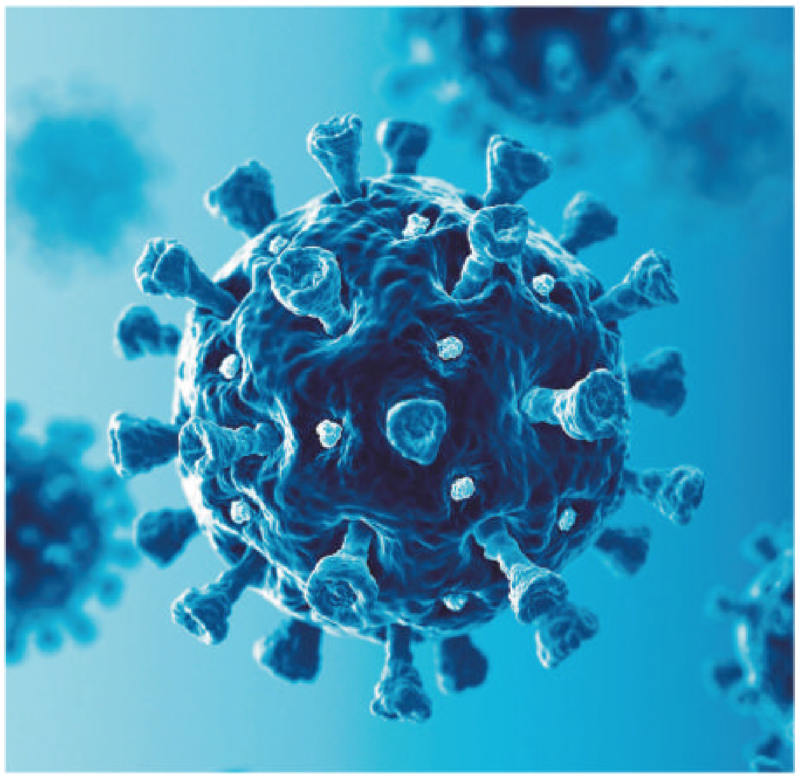
Remarkably, there is now hard evidence to back Allen's idea: we have found one of those rare manganese-rich environments. Woodward Fischer at the California Institute of Technology in Pasadena and his colleagues have studied rocks laid down in what is now South Africa just before levels of oxygen began to rise. In one spot, they found a superabundance of manganese oxide in rocks that formed – significantly – in the absence of oxygen. Not even ultraviolet light could have generated manganese oxide on the scale found in the rocks. The researchers' conclusion was that photosynthesis as it existed in Allen's proto-cyanobacteria is the only plausible scenario.

What would settle the debate once and for all is the discovery of living representatives of one of the proposed intermediate forms – either indigo bacteria or proto-cyanobacteria. Blankenship and Allen are both confident that their respective organisms still exist somewhere in the world.

Whatever the ancestor of cyanobacteria turns out to be like, we have reason to be very grateful to it. It helped create the world we live in. ∎

VIRUSES: ANOTHER KIND OF LIFE

A further group of microscopic organisms has thrived on Earth since the early days: viruses. They are almost undoubtedly the most numerous and diverse living entities on Earth. Their mysteries start with whether they truly count as living.



Whether viruses are truly alive is a question to which there is no simple answer

BLACKJACK3D/ISTOCK

THE vast majority of viruses are little more than strands of genetic material packaged up in a protein container called a capsid. Around a quarter are also surrounded by an envelope, which is usually made of a lipid membrane stolen from its host plus some virus-encoded proteins.

A single virus is called a virion. Most are around 100 nanometres across. Their sole aim in (quasi-)life is to invade the cells of their host, release their genetic material and hijack the cell's biochemistry to make more copies of themselves. The new virions then burst out of the cell, killing it, and begin the cycle anew. Viruses are genetic parasites.

That leads to the question of whether they are truly alive, to which there is no simple answer. On the one hand, they are biological entities that reproduce themselves, which fulfils at least a minimal definition of life. On the other hand, they don't have an independent metabolism and are totally unable to reproduce outside of their host. Evolutionary biologists don't consider them to be part of the universal tree of life. It is probably best to think of them as quasi-alive.

Whatever the answer to that, viruses are hugely varied. Some are so simple that they can be described using a (relatively complex) chemical formula. A polio virion, for example, consists of a short piece of RNA wrapped in a single-protein capsid and has the chemical formula $C_{332,652} H_{492,388} N_{98,245} O_{131,196} P_{7501} S_{2340}$. Others are as large and complex as a bacterium, with hundreds or even thousands of genes and a complex capsid and envelope. The first of these giant viruses were discovered only in 2003, and shook up the world of virology, challenging the idea that viruses are merely non-living bags of chemicals. Some viruses even have pathogenic viruses themselves.

We usually think of viruses as pathogens of both animals and plants, and indeed many of the well-known ones cause diseases, including some of the worst ever: smallpox, polio, influenza, Ebola, rabies, AIDS, Zika and, of course, covid-19. Measles, chickenpox, herpes and the common cold are also viral diseases. But most viruses are probably benign parasites that "live" and reproduce inside of us and other life forms without ever coming to our attention.

And for sheer abundance, no other group of organisms matches them. One study estimates the population of viral particles in the oceans alone is as high as 10^{30}. Another puts the total virus population on Earth an order of magnitude higher than that, at 10^{31}, or over a million times more than the estimated number of stars in the universe. According to research published in 2019, each day some 800 million viruses attached to dust particles fall onto every square metre of Earth's surface – and we know almost nothing about most of them.

A new field of study known as viral ecology is providing insights into the interactions between viruses and their hosts. It is a gargantuan task.

›

Consider, for instance, the human microbiome: the vast array of microorganisms that live in and on every one of us. Our bodies contain hundreds of different cell types – including those that make up our complex immune systems and that constantly try to fight off alien organisms – all of which interact with the thousands or even millions of types of viruses and bacteria in our microbiome. Add the fact that these microbes can both help and compete with one another, and the number of possible interactions might as well be infinite.

Nevertheless, we are starting to see the bigger picture of viral ecology. A 2017 study offered the first map of virus-host networks covering all viral species then known. The authors looked at the distribution of viruses in different environments and their movements between them. The study also revealed that most viruses have a surprisingly narrow range of habitats, infecting only one or two types of host. Another study from 2017 shed light on an enigmatic part of the virosphere, a whole other world of viruses that infect a domain of single-celled organisms called archaea.

This is just the tip of the iceberg, however. While we have long suspected that viruses are the most diverse group of organisms on Earth, we still have only the vaguest idea of exactly how many types there are. In the past two decades, more have been identified than ever before. As of 2019, researchers had identified 195,000 species of virus, nearly 20 times more than were known in 2015. Given that viruses tend to be specialised to just a few hosts, their diversity is likely to be far greater than all other species put together.

The recent advances in our knowledge of viral diversity have been enabled by the advent of metagenomics, which allows researchers to identify viral genes present in an environmental sample without having to isolate individual organisms. They literally scoop up seawater or soil and analyse it to see how much viral genetic material it contains. But there is a downside: the findings contain lots of unidentified sequences, dubbed "dark matter". Currently, it is difficult to work out what this dark matter actually is. Assigning genes to a particular species of virus is made even harder because of the incredible rate at which these organisms evolve. To properly analyse viruses, we need to be able to "see" them. That will require looking at features beyond genetic sequences, such as the structure of virus proteins.

Another problem with mapping the virosphere is that researchers are unsure how to categorise viruses. At the moment, they use a system similar to the one used to classify all organisms, with categories ranging from kingdom (viriae) to genus and species. So far, fewer than 5000 viruses have been classified in this way. What's more, there is a growing realisation that the current classification system has vast gaps and is wrong in places.

There is a push to do something about this, though. In 2020, researchers from the International Committee on Taxonomy of Viruses called for classification of the entire virosphere. They acknowledged that this is a massive undertaking, but argued that the potential benefits are huge. "We cannot know what the trove of 'unimportant' viruses could possibly amount to until we have examined them," they wrote in *Nature*. "Virus classification is a straightforward way to contribute today to solving the global problems of tomorrow."

That may sound grandiose, but it is justified. Viruses aren't simply a threat to people's health and livelihoods, they are also essential to life on Earth. What they offer, evolutionary biologists are starting to realise, is access to new genetic material that can help organisms adapt and survive.

Viruses evolve much more quickly than any other known entity – as much as a million times faster than we do – giving them a constant supply of new genetic material. They can share these genes with their hosts in a process called horizontal gene transfer. Think of it as a trading game where players can swap cards to improve their deck. Two players will soon have both acquired the best possible combinations. But if they can swap with new players with rapidly changing decks (viruses), they can build a far more competitive hand.

Horizontal gene transfer with viruses doesn't help individual people directly, as our genome is pretty much defined from conception. But gene swapping may help to explain the complexity of life on Earth: fast evolution, coupled with the ability to trade genes, allows simple organisms to quickly adapt to almost any environment. This was crucial for the earliest forms of life – and viruses may have played an important part in their success. So learning more about the relationships between viruses, hosts and their environments should give us key insights into the evolution of life and even its origins.

In addition, studies of viral ecology can help us understand – and one day possibly even predict – the outcomes of interactions between viruses and their hosts. The benefits are clear when that host is us. One large-scale scheme, known as the Global Virome Project, aims "to detect the majority of our planet's unknown viral threats" to predict which viruses are likely to jump hosts to infect and possibly kill us. Anyone who has lived through the past few years doesn't need reminding how important that is. ∎

UNSW SYDNEY

WHERE DID VIRUSES COME FROM?

The origin of viruses is contentious, with broadly three competing ideas. One is that viruses predate cells. In this view, viruses emerged from the primordial soup as free-living, self-replicating entities in a precellular "virus world". Only later did they become parasitic, once cells had evolved.

A second possibility is that some cells evolved simpler forms and became viruses. In this scenario, cells came first and viruses have only ever existed alongside cells. A third notion, related to the second, is that cells came first and that viruses were cellular components that "escaped" to become autonomous parasites. It may be that certain genes escaped from cells and became viruses.

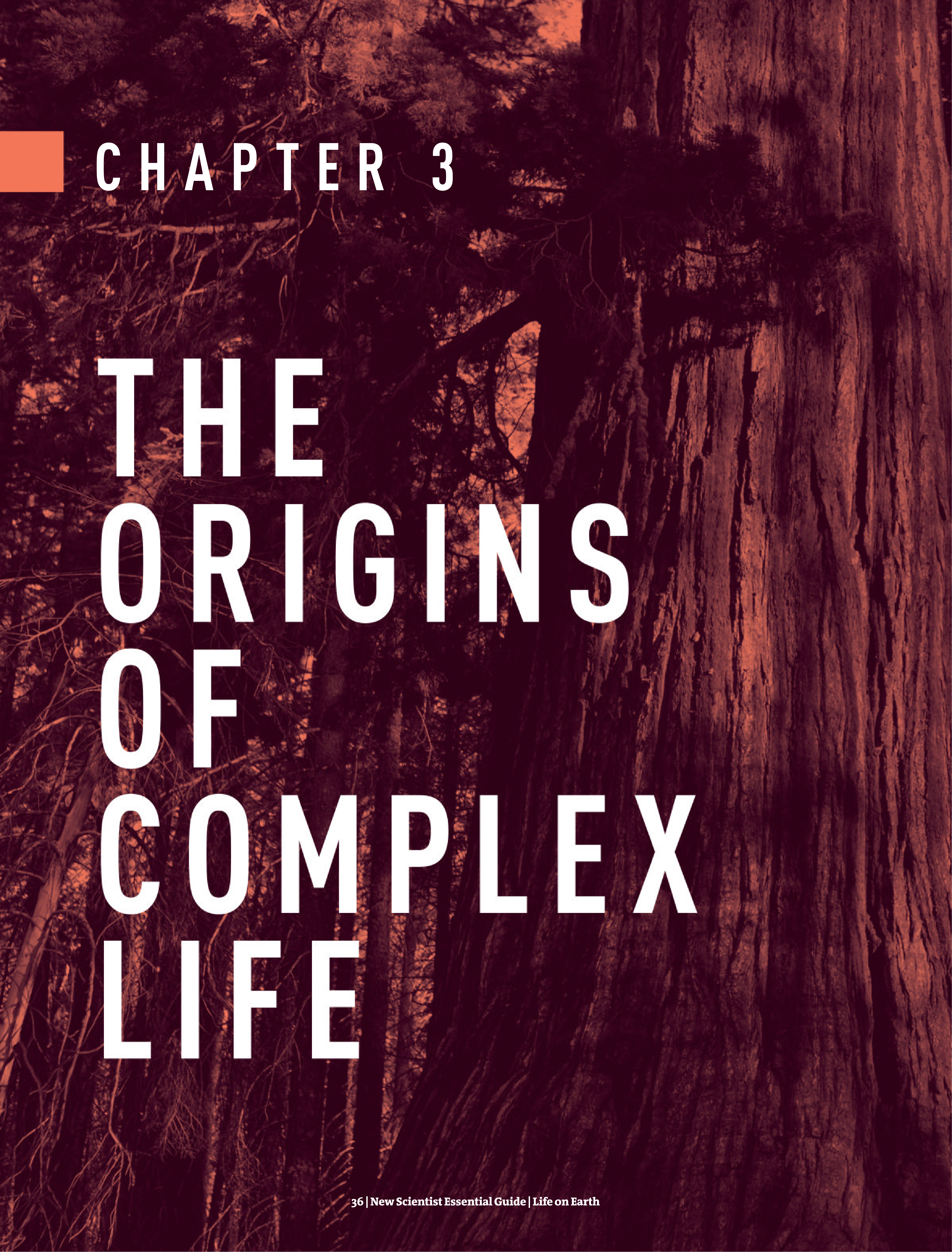
Conceivably, all these ideas are true. There is evidence that viruses don't have a single common ancestor, but instead originated several times. Nevertheless, the third or "escape" hypothesis has gathered support in recent years. In 2017, a study suggested that many capsid proteins essential for the packaging of a virus can be traced back to proteins found in cells.

Ricardo Cavicchioli at the University of New South Wales in Australia and his colleagues found a microorganism in the lakes of the Rauer Islands off the coast of Antarctica that might shed some light on the question. The organism, which they named *Halorubrum lacusprofundi* R1S1, is a single-celled archaeon.

The group knew that viruses often play an important role in Antarctic ecosystems, so team member Susanne Erdmann searched for viruses inside the organism's cells. She found something unexpected: a plasmid. Plasmids are small fragments of DNA, often circular, that reside in living cells. They aren't part of the cell's main genome and can replicate themselves independently. Often, a plasmid will carry a gene that is somehow useful to the cell: for instance, antibiotic resistance genes are sometimes found on plasmids.

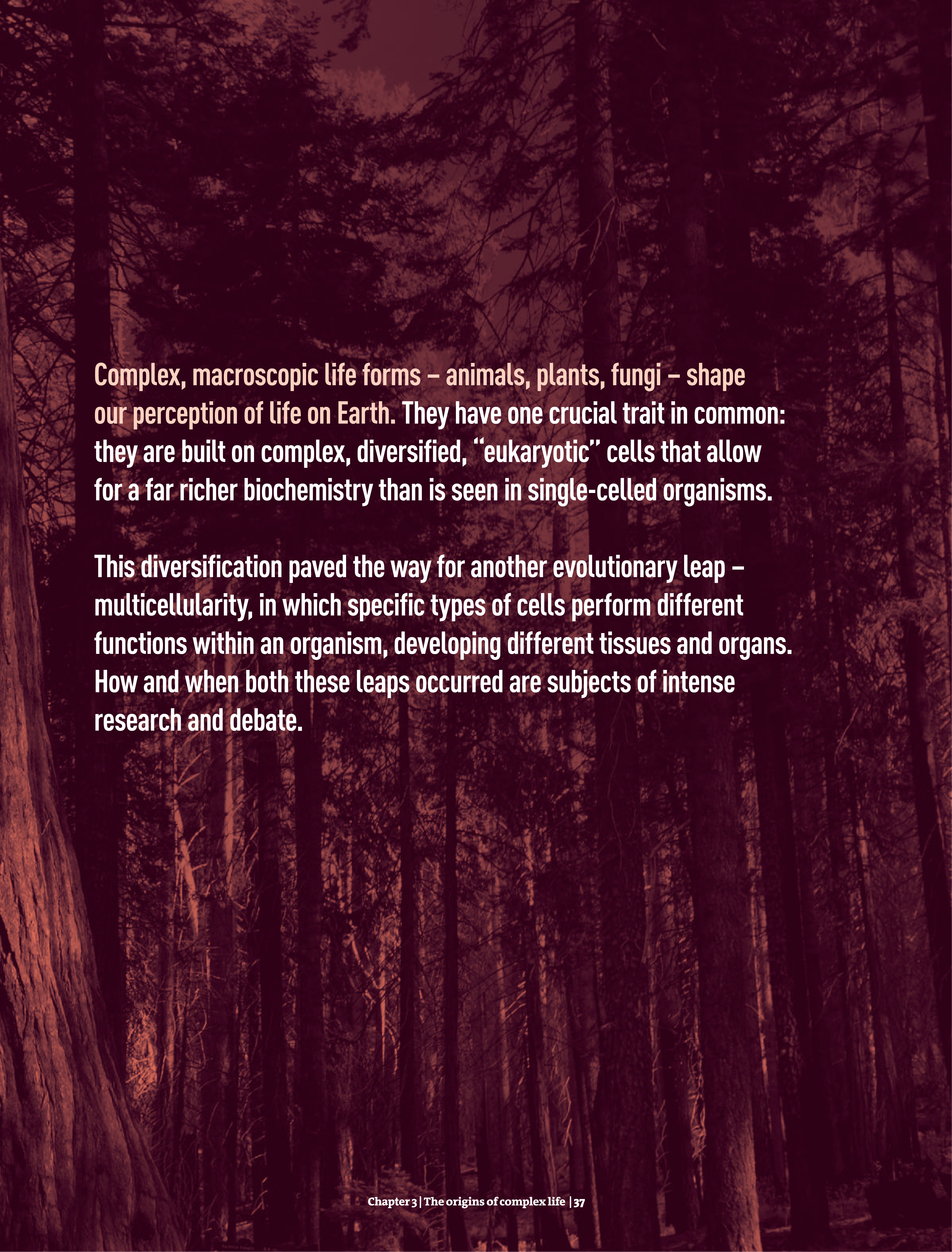
The plasmid Erdmann found, which the team calls "pR1SE", is unusual. The genes it carries allow it to make vesicles – essentially bubbles made of lipids – that enclose it in a protective layer. Encased in its protective bubble, pR1SE can leave its host cell to seek out new hosts.

In other words, pR1SE looks and acts a lot like a virus. But it carries genes that are found only on plasmids and lacks telltale virus genes. It is a plasmid with the attributes of a virus. Cavicchioli suggests that viruses could have evolved from plasmids like pR1SE, by acquiring genes from their host that allowed them to make a hard capsid shell rather than a soft vesicle. If that is so, the first viruses escaped from some of the first living cells on Earth.



CHAPTER 3

THE ORIGINS OF COMPLEX LIFE



Complex, macroscopic life forms – animals, plants, fungi – shape our perception of life on Earth. They have one crucial trait in common: they are built on complex, diversified, “eukaryotic” cells that allow for a far richer biochemistry than is seen in single-celled organisms.

This diversification paved the way for another evolutionary leap – multicellularity, in which specific types of cells perform different functions within an organism, developing different tissues and organs. How and when both these leaps occurred are subjects of intense research and debate.

THE FIRST COMPLEX CELLS

Besides bacteria and archaea, there is a third great domain of life: the eukaryotes, which includes all animals, plants and fungi. The individual cells of these organisms, including our own, have a diversified interior that allows for a far more intricate biochemistry. Complexity was a great innovation, but how these cells first appeared seems to have been an evolutionary accident.

MISHA KAMINSKY/ISTOCK
PREVIOUS PAGE: PGIAM/ISTOCK

OUR living planet, Charles Darwin wrote in *On the Origin of Species*, is one of "endless forms most beautiful". But as we have seen, go back a couple of billion years and things would have looked very different. The most complex life was colonies of microbes such as stromatolites and microbial mats. No plants, no animals, just a barren landscape of rock, river and ocean.

For many years, biologists assumed that the emergence of complex life was an evolutionary inevitability. Once simple life emerged, it gradually evolved into more complex forms, eventually giving rise to animals and plants. But that doesn't seem to be what happened.

If simple cells had slowly evolved into more complex ones over billions of years, all kinds of intermediate cells would have existed and some still should. But there are none. Instead, there is a yawning gulf. On one side, there are the tiny bacteria and archaea, collectively known as prokaryotes. On the other side, there are the huge and unwieldy eukaryotes, the third great domain of life. A typical single-celled eukaryote, such as an amoeba, is about 15,000 times larger than a bacterium, with a genome to match.

Prokaryotes are little more than tiny bags of chemicals – complex bags, to be sure, but nothing compared with eukaryotic cells, which boast miniature organs called organelles, internal membranes,

›

LUCKY-PHOTOGRAPHER/ISTOCK PHOTO

Complex cells must aggregate and cooperate to make something like a giant sequoia

skeletons and transport systems. They are to prokaryotes what a human is to an amoeba.

And while bacteria never form anything more complex than chains or colonies of identical cells, eukaryotic cells aggregate and cooperate to make everything from seaweed to sequoias, aardvarks to zebras. All complex multicellular life forms – that is to say, pretty much every living thing you can see around you, and more besides – are eukaryotes.

The sudden appearance of complex cells from nowhere is redolent of an evolutionary accident. The critical event appears to have occurred when one simple cell somehow ended up inside another. The identity of the host cell isn't clear, but we know it engulfed a bacterium, which began to live and divide within it, like a squatter. The two somehow found a way to live together amicably, and eventually formed a symbiotic relationship called endosymbiosis.

Through co-evolution over countless generations, the endosymbionts eventually became an organelle called the mitochondrion. These stripped-down vestiges of their former bacterial selves evolved to have one key function: to supply the cell with energy. This was the critical step that allowed life to throw off its microbial shackles and evolve into endless forms most beautiful.

Once they have mitochondria, cells can overcome a fundamental barrier that prevents bacteria and archaea from growing large. In a nutshell, there is a limit to how much energy microbes can produce. The cell's universal energy currency, ATP, is manufactured at the cell membrane. But as cells grow larger, their surface area-to-volume ratio drops and they have relatively less membrane to use. As they grow larger, their energy demands quickly overtake the supply. A cell with mitochondria (which have their own ATP-making membranes) can overcome this simply by adding more mitochondria – something that is easily done, as the mitochondria retain their bacterial ancestors' ability to clone themselves.

←
Turn back to page 12 for more on how life gets its energy

Awash with squadrons of mitochondria cranking out energy, early eukaryotes were free to grow larger and accumulate bigger and more complex genomes. And these expanded genomes provided the genetic raw material that permitted the evolution of ever more complex life.

That wasn't the end of the story. Another round of endosymbiosis is thought to have created the chloroplast, the organelle that allows plants and algae to convert sunlight into sugar in a process called photosynthesis. The endosymbiont in this case was a photosynthetic bacterium.

←
Page 28 has more on the evolution of photosynthesis

The cell nucleus, where cells store the majority of their DNA, was another crucial invention. It may have been created by another endosymbiosis, possibly involving a virus. Eukaryotic cells also acquired other organelles, such as the endoplasmic reticulum, where proteins are made, and the Golgi apparatus, which dispatches them to their destination, possibly by infolding of their cell membranes.

Still, the mitochondrion looks to have come first. For many biologists, mitochondria are the defining feature of eukaryotes. They unite single-celled eukaryotes like amoeba with giant redwoods, toadstools and human beings. ▮

WHEN DID EUKARYOTES EVOLVE?

The origin of eukaryotes is one of the most important and mysterious events in the entire history of evolution – and we are finally getting some clues as to when it happened.

THE date of "eukaryogenesis" is still highly uncertain, but most evidence puts it at between 1.8 billion and 1.2 billion years ago. That is a fascinating piece of timing.

Conventional wisdom has it that evolution stalled after the upheaval of the Great Oxidation Event around 2.4 billion years ago, when oxygen-producing, photosynthesising organisms fundamentally changed Earth's chemistry. Life's history was considered so dull that the period between 1.8 billion and 800 million years ago has been dubbed the "boring billion". In fact, it was nothing of the sort.

There is also clear evidence that there was a single origin for eukaryotes – they all (we all) evolved from the same ancestor. Without that one-off event, life would still be stuck in its microbial rut, with nothing but bacteria and archaea roaming Earth. This has cosmic implications. If the origin of complex life was a freak event that only happened once, it suggests that complex life is rare in the universe. Although other planets could be home to simple cells, these might thrive for aeons without complex life ever arising.

So much for the when: what about the how? We have seen that eukaryotes arose not through competition, which drives so much of evolution, but by cooperation: an archaeon is thought to have swallowed a bacterium and the two organisms managed to live as one, with the bacterium becoming the first mitochondrion. Quite how this happened is still debated, but we may know more soon by studying a recently discovered group of organisms.

Their story begins in the depths of the sea. In 2008, a team of researchers was struggling to find a group of hydrothermal chimneys at the bottom of the Norwegian Sea because the heat signature seemed to keep shifting. When they finally tracked down the rocky spires, they thought it would be apt to name them Loki's Castle – in reference to the Norse trickster god Loki's ability to confound those around him by shapeshifting.

←
See page 15 for more on the importance of hydrothermal vents to life

The castle's smallest residents soon began stirring up trouble too. In a 2015 study, Thijs Ettema at Uppsala University, Sweden, and his team analysed DNA extracted from underwater sediment near Loki's Castle. They found DNA from a new type of archaea, which they called Lokiarchaeota.

Archaea and bacteria collectively make up the prokaryotes. Both lack a true cell nucleus and other complex cell machinery. But intriguingly, the Lokiarchaeota appeared to have more than 100 genes coding for sophisticated cellular functions, such as deforming cell membranes and forming and transporting bubble-like vesicles around the cell, functions that are usually only seen in eukaryotes like us.

The discovery suggested that our sophisticated cells could have evolved from special, more elaborate forms of ancient prokaryote. Furthermore, the ›

Lokiarchaeota's DNA showed that they were our closest known relatives among the prokaryotes. Later studies found other related archaea, which have been named after other figures from Norse mythology. For instance, in 2019, Gerdarchaeota – named for the Norse goddess of fertile soils – were identified in coastal sediments. The group as a whole is now called the Asgard archaea, after the home of the Norse gods.

Unfortunately, Ettema and his team didn't actually see the cells: they used computational methods to piece together the genomes from the DNA found in the sea-floor sediment. The challenge was to grow them in a laboratory, so that their behaviour could be observed. Archaea can be particularly difficult to collect and culture in a laboratory, so the prospects looked poor – except it turned out that another group had been working on that exact problem for years.

In 2006, before anyone had heard of Asgard archaea, a Japanese team collected a sediment core from an area of seabed some 2500 metres down in the Nankai Trough off Japan's southern coast. Later that year, Hiroyuki Imachi at the Japan Agency for Marine-Earth Science and Technology and his colleagues began trying to grow microorganisms from the sample in an incubator.

After hearing Ettema talk about Asgard archaea at a conference in 2014, Imachi worked with his colleagues to devise a special mixture of nutrients and other chemicals that enabled an Asgard archaeon to be grown and studied in a lab for the first time.

Imachi calls the new microbe *Prometheoarchaeum syntrophicum*. The researchers have photographed the microbes and studied their behaviour, announcing their results in a preprint in 2019 and in a scientific journal the following year.

Two features of *Prometheoarchaeum* leap out as significant. The first is that it doesn't live on its own. Imachi's team could only grow it alongside at least one other microbe, and preferably two: another archaeon called *Methanogenium* and a bacterium called *Halodesulfovibrio*. Experiments indicate that *Prometheoarchaeum* breaks down amino acids into simpler chemicals, including hydrogen, which the other microbes then eat. Organisms that eat one another's wastes are called syntrophs. Close partnerships like these could have been a stepping stone for Asgard archaea towards swallowing cooperative microbes into their cells.

Secondly, *Prometheoarchaeum* is an unusual shape for an archaeon. It has long arms, a bit like the tentacles of an octopus, and its microbial partners nestle within these. Imachi suggests that these arms explain how complex cells originated. If an Asgard archaeon had bacteria in its arms, and the arms fused into a single lump, the bacterium would have ended up inside the Asgard archaeon.

We don't yet know if all Asgard archaea have these arms, but nevertheless evidence is mounting. For instance, Robert Robinson at Okayama University in Japan and his team have found that Asgard archaea have complex mechanisms for assembling and breaking down a protein called actin.

This had been predicted on the basis of the microbes' DNA, but Robinson's team showed how the system works. It even functions when transferred into human cells, which suggests that this molecular machinery has changed very little, even over billions of years.

Actin forms struts within cells, so it is crucial for their ability to change shape by deforming their outer membranes – which is necessary for swallowing other cells. Robinson says Asgard archaea probably use actin to grow their protrusions.

This is neat, but it can't explain everything, says Purificación López-García at the French National Centre for Scientific Research. She says the outer membranes of eukaryotes resemble those of bacteria, not those of archaea – which makes no sense if eukaryotes are primarily descended from Asgard archaea. Many eukaryotic genes also come from bacteria. She suspects that more than two microorganisms contributed to eukaryotes.

In line with this, a Japanese group recently described a bacterium that can engulf other microorganisms. This ability was thought to be unique to eukaryotes. But if it turns out to be more widespread, Asgard archaea may be just one player in a larger story of microbes swallowing each other during the origin of eukaryotes. ▮

FROM ONE CELL TO MANY

With the evolution of eukaryotes, life on Earth was able to take another big leap – it could become multicellular, and thus far more complex. But how did single cells that lived solitary lives wind up joining together with their neighbours and subsuming their identity into that of a larger body?

UNTIL the 1950s, the oldest known multicellular organisms were from the Cambrian Period, which started 541 million years ago. Geologist Reg Sprigg found fossils that later turned out to be Precambrian at Ediacara in the Flinders Ranges of South Australia in 1946, but received little attention. Then, in 1957, some English schoolchildren discovered a fossil, which was the first recognised "Ediacaran" – a weird, multicellular organism that lived between 635 million and 542 million years ago. But even Ediacarans weren't the first multicellular organisms.

In 2016, a team led by Shixing Zhu at the China Geological Survey described rectangular and tongue-shaped blobs that were up to 30 centimetres in length. They look like primitive seaweed and were found in rocks from the Gaoyuzhuang Formation in northern China that dated back 1.56 billion years. Fragments of preserved cellular material revealed the cells to be organised in tightly packed sheets, not in loose colonies, strongly suggesting that they were true multicellular organisms.

There are claims of even older examples of multicellularity, which would push back the date of the first complex cells, too. In 2010, a team reported 2.1 billion-year-old fossils in Gabon that also looked a bit like multicellular organisms. The fossils were up to 12 centimetres in size and were shaped like flat discs with ruffed edges – unlike any species alive today. But they aren't as well preserved as the Gaoyuzhuang fossils and some researchers argue that they look more like marks left by bacterial colonies. Then there are Grypania, centimetre-sized, tube-shaped fossils that appear in the fossil record about 1.8 billion years ago. However, most experts also think these are clumps of bacteria, not multicellular beings.

Even leaving these outliers to one side, this brings a new puzzle. Instead of wondering why multicellular organisms took so long to evolve, the question becomes why it took them a billion years after they first evolved to develop into the more complex forms of the Ediacarans. Perhaps oxygen levels had to rise still further. Or maybe evolution was slowed in its tracks by a "snowball Earth" period of plunging temperatures that occurred between 720 million and 635 million years ago. However, the microfossil record shows little evidence of species being wiped out at that time. Indeed, it has been argued that some organisms thrived on Earth's icy surface.

The origin of multicellularity seems, on the face of it, to be as unlikely an evolutionary leap as the origin of eukaryotes. But gathering evidence suggests that it isn't a huge hurdle. Notably, multicellularity has evolved at least 20 times since life began – unlike eukaryogenesis, which seemingly only happened once. This indicates it is something evolution can do with relative ease.

However, the last instance was about 200 million years ago, leaving few clues to the precise sequence of events. To understand the process better, William ›

Ratcliff – now at the Georgia Institute of Technology in Atlanta – and his colleagues set out to evolve multicellularity in a common unicellular lab organism, brewer's yeast.

Their approach was simple: they grew the yeast in a liquid and gently centrifuged each culture once per day, inoculating the next batch with the yeast that settled out on the bottom of each tube. Just as large sand particles settle faster than tiny silt, groups of cells settle faster than single ones, so the team effectively selected for yeast that clumped together.

Sure enough, within 60 days – about 350 generations – every one of their 10 culture lines had evolved a clumped, "snowflake" form. Crucially, the snowflakes formed not from unrelated cells banding together, but from cells that remained connected to one another after division, so that all the cells in a snowflake were genetically identical relatives. This relatedness provides the conditions necessary for individual cells to cooperate for the good of the whole snowflake. This is crucial, because for multicellularity to become fixed, natural selection needs to start operating on groups of cells rather than on single cells. Once that has happened, the groups can be thought of as primitive multicellular organisms.

In some ways, the snowflakes do behave as if they are multicellular. They grow bigger by cell division and when the snowflakes reach a certain size, a portion breaks off to form a daughter cell. This "life cycle" is much like the juvenile and adult stages of many multicellular organisms.

After a few hundred further generations of selection, the snowflakes also began to show a rudimentary division of labour. As the snowflakes reach their "adult" size, some cells undergo programmed cell death, providing weak points where daughters can break off. This lets the snowflakes make more offspring while leaving the parent large enough to sink quickly to the base of the tube, ensuring its survival. Snowflake lineages exposed to different evolutionary pressures evolved different levels of cell death. Since it is rarely to the advantage of an individual cell to die, this is a clear case of cooperation for the good of the larger organism – a key sign that the snowflakes are evolving as a unit.

Sceptics, however, pointed out that many yeast strains naturally form colonies, and that their ancestors were multicellular tens or hundreds of millions of years ago. As a result, they may have retained some evolved mechanisms for cell adhesion and programmed cell death, effectively stacking the deck in favour of Ratcliff's experiment. Even so, much of evolution proceeds by co-opting existing traits for new uses – and that is exactly what Ratcliff's yeast did.

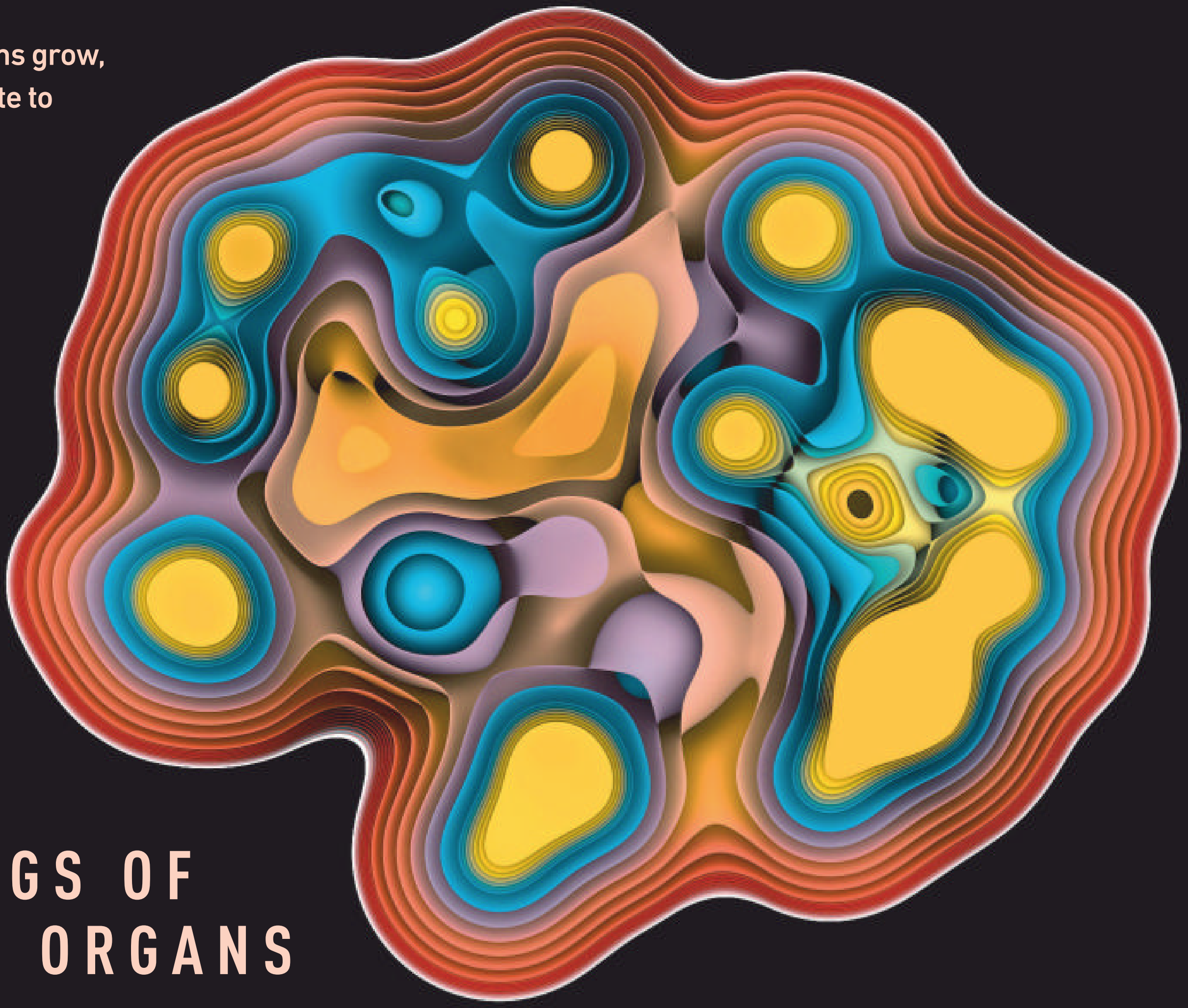
In follow-up experiments, Ratcliff and his team dug into the details of how the brewer's yeast made the transition. It seems there is more than one way this can happen. In 2015, they showed that the transformation from a single to multicellular existence could be driven by a single gene called ACE2 that controls the separation of daughter cells after division. And because the snowflake grows in a branching, tree-like pattern, any later mutations are confined to single branches. When the original snowflake gets too large and breaks up, these mutant branches fend for themselves, allowing the value of their new mutation to be tested in the evolutionary arena.

Ratcliff's team has also evolved multicellularity in single-celled algae called *Chlamydomonas*, through similar selection for rapid settling. The algal cells clumped together in amorphous blobs.

That feat was later repeated, but with predators thrown into the mix. A team led by Matt Herron at the University of Montana in Missoula exposed *Chlamydomonas* to a *Paramecium*, a single-celled protozoan that can devour single-celled algae but not multicellular ones. Sure enough, two of Herron's five experimental lines became multicellular within six months, or about 600 generations. This time, instead of daughter cells sticking together in an amorphous blob as they did under selection for settling, the algae formed predation-resistant, spherical units of four, eight or 16 cells that look almost identical to related species of algae that are naturally multicellular.

Neither Ratcliff's yeast nor Herron's algae unequivocally crossed the critical threshold to multicellularity, which would require cells to divide labour between them. But the experiments are an important step along that road. ▮

As multicellular organisms grow, their cells can differentiate to form internal structures



BEGINNINGS OF INTERNAL ORGANS

True multicellular organisms aren't just clumps of cells stuck together. Different cells can evolve specialised functions, so they share the labour of maintaining the organism, creating distinct tissues and organs.

A tiny organism that lived a billion years ago may have been one of the first life forms built that way. It had two different cell types, one forming its core and another its outer "skin". making it a crucial step towards modern organisms like animals that also have a skin that is distinct from the cells inside the body.

Evidence for this species, dubbed *Bicellum brasieri*, comes from microfossils preserved in rocks that formed in an ancient freshwater lake in north-west Scotland, found by Charles Wellman at the University of Sheffield, UK, and his colleagues. Each instance was a clump of a few dozen cells a few tens of micrometres across. There was a central ball of tightly packed oval cells, surrounded by an outer layer of sausage-shaped cells.

Some of the fossils only had the central ball. The team suggests these show the organism in a larval stage. "The cells keep dividing to form this ball of cells and then different cells form in it that elongate, and these appear to migrate to the outside and form an outer layer," says Wellman.

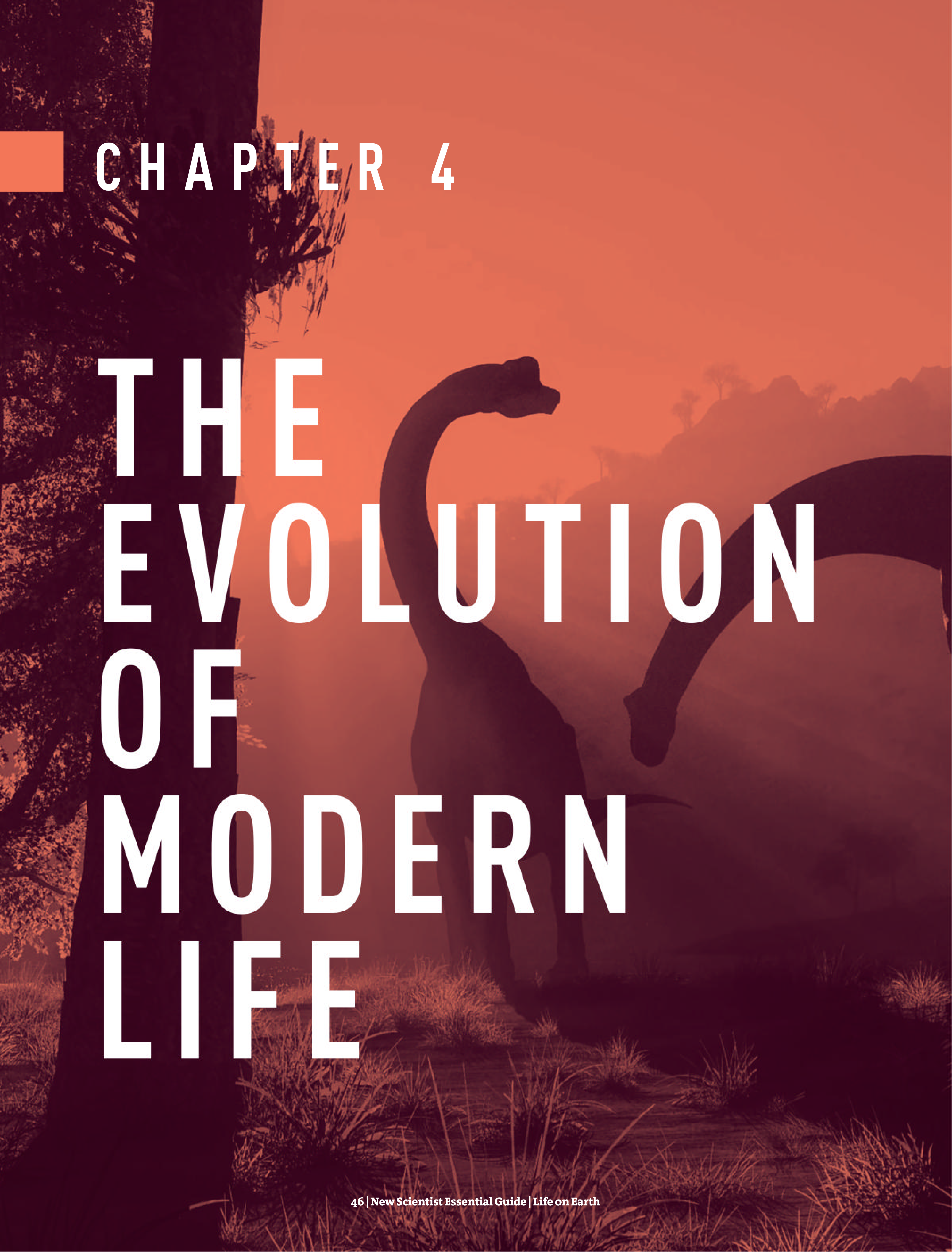
The team believes the two cell types might be explained by basic physics. The late biologist Malcolm Steinberg argued that if some cells stick together better than others, that will be enough to generate quite complex structures, an idea he called the differential adhesion hypothesis. For Wellman, the structure of *B. brasieri* is compatible with this idea.

B. brasieri wasn't a true animal, emphasises Wellman. But it probably belonged to the larger group from which animals arose.

For Emily Mitchell at the University of Cambridge, UK, the "million-dollar question" is why it took multicellular organisms hundreds of millions of years to give rise to complex animals like sponges, jellies and worms.

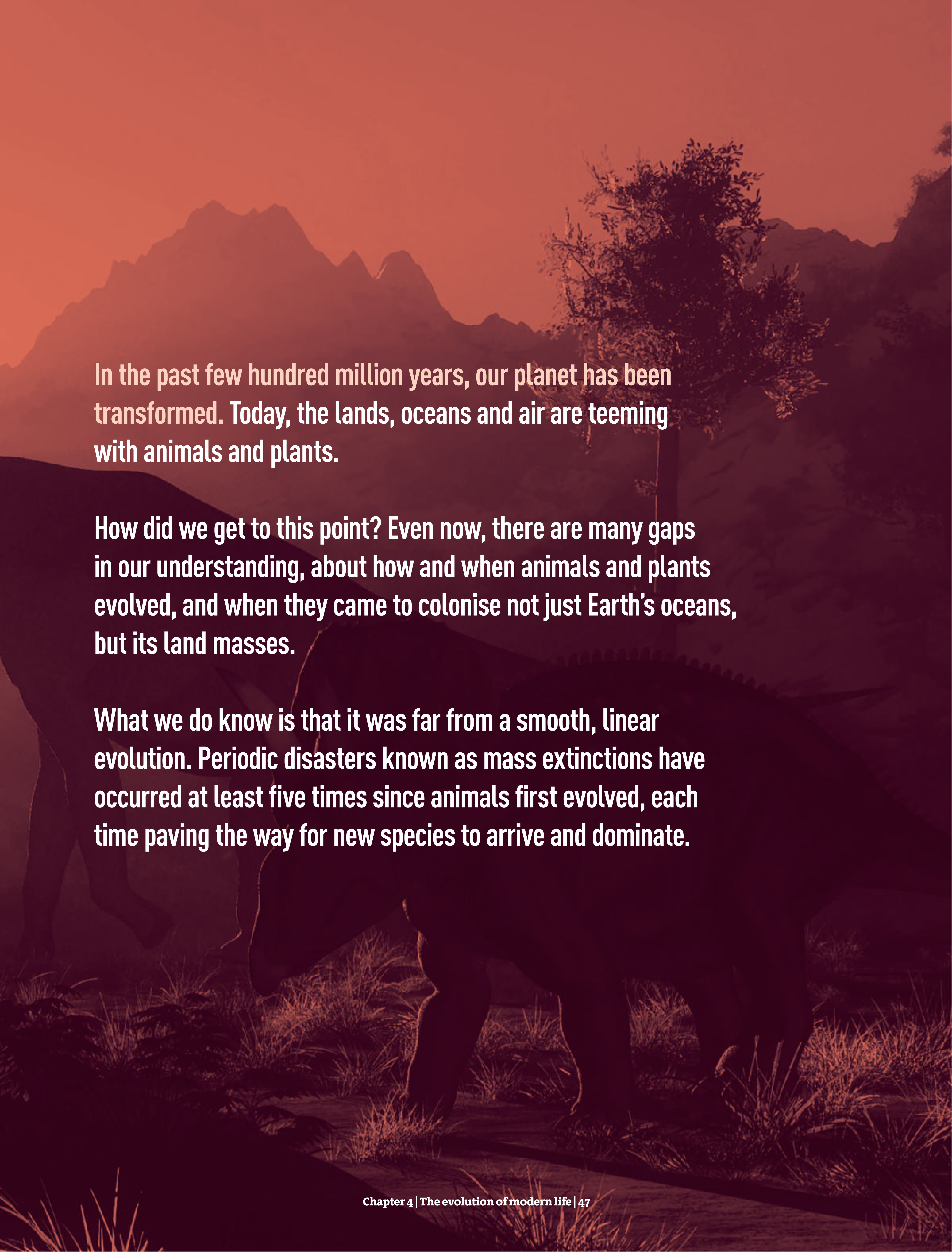
For many years, it was assumed that an increase in oxygen levels around 550 million years ago enabled the rise of animals, but in recent years, evidence has emerged that ancient animal groups like sponges can survive at low oxygen levels – and that the oxygen level only rose after the first animals had appeared some 600 million years ago. That means the oxygen rise can't be the explanation for the origin of animals.

BENNU PHOENIX/ALAMY STOCK PHOTO



CHAPTER 4

THE EVOLUTION OF MODERN LIFE



In the past few hundred million years, our planet has been transformed. Today, the lands, oceans and air are teeming with animals and plants.

How did we get to this point? Even now, there are many gaps in our understanding, about how and when animals and plants evolved, and when they came to colonise not just Earth's oceans, but its land masses.

What we do know is that it was far from a smooth, linear evolution. Periodic disasters known as mass extinctions have occurred at least five times since animals first evolved, each time paving the way for new species to arrive and dominate.

THE FIRST ANIMALS

From elephants to electric eels, today the world is teeming with animal life. Broadly defined as organisms that are multicellular, capable of locomotion and responsive to their environment, the first animals evolved more than 500 million years ago – and they were very strange indeed.

FOR many years, the story of the origin of animals went like this. Life appeared on our planet more than 3.5 billion years ago and consisted exclusively of microbes for the next 3 billion years. Then, about 539 million years ago, everything changed. In the geological blink of an eye, the seas were filled with large and complex animals, including worms with legs and fearsome spikes; creatures with a trunk-like nose and five eyes; and giant shrimp-like predators with mouths like pineapple rings.

This evolutionary starburst is known as the Cambrian explosion. It has traditionally been seen as one of the most significant moments in life's history on Earth – evolution's "big bang", the point at which species that are clearly related to today's animals first appeared.

Over the past few years, however, geologists have begun to have second thoughts. Newly discovered fossils and careful analysis of ones found decades ago suggest that animals were thriving in the period before the Cambrian explosion. As a result, some people are now arguing that the explosion of animal life started about 12 million years earlier. Others are questioning whether it is possible to define a distinct explosion at all.

You could forgive for thinking that shifting the dawn of the animal revolution from 539 million to 551 million years ago isn't that big a deal. But

RICHARD BIZLEY/SCIENCE PHOTO LIBRARY
PREVIOUS PAGE: ALLVISIONN/IPHOTO

BIZLEY

evolution can do a lot in that length of time: the entire span of human evolution probably fits within 12 million years, the length of time since our lineage separated from that of chimpanzees. What's more, shifting life's big bang back could have important implications for the quest to figure out what sparked evolution's most spectacular spell of invention.

Scholars first worked out how to read the geological record in the 19th century, and they quickly noticed something puzzling. The oldest rocks they could find seemed devoid of fossils. Biologically complex marine animals, including woodlouse-like trilobites, suddenly appeared in abundance in the rocks assigned to the Cambrian period.

The pattern troubled Charles Darwin because it clashed with his idea of evolution by natural selection as a slow and gradual process. To make sense of it all, he suggested that simpler life forms must have evolved before the Cambrian, but left little or no fossil evidence of their existence.

We now know Darwin's hunch was correct. As we have seen, geologists have spotted signs of microbial life in rocks that are more than 3 billion years old, and have also identified an important subsequent transition when those microbes became slightly larger and more biologically complex.

←
Chapter 2 concerns the evolution of simple microbial organisms

←
Chapter 3 covers the evolution of complex multicellular life

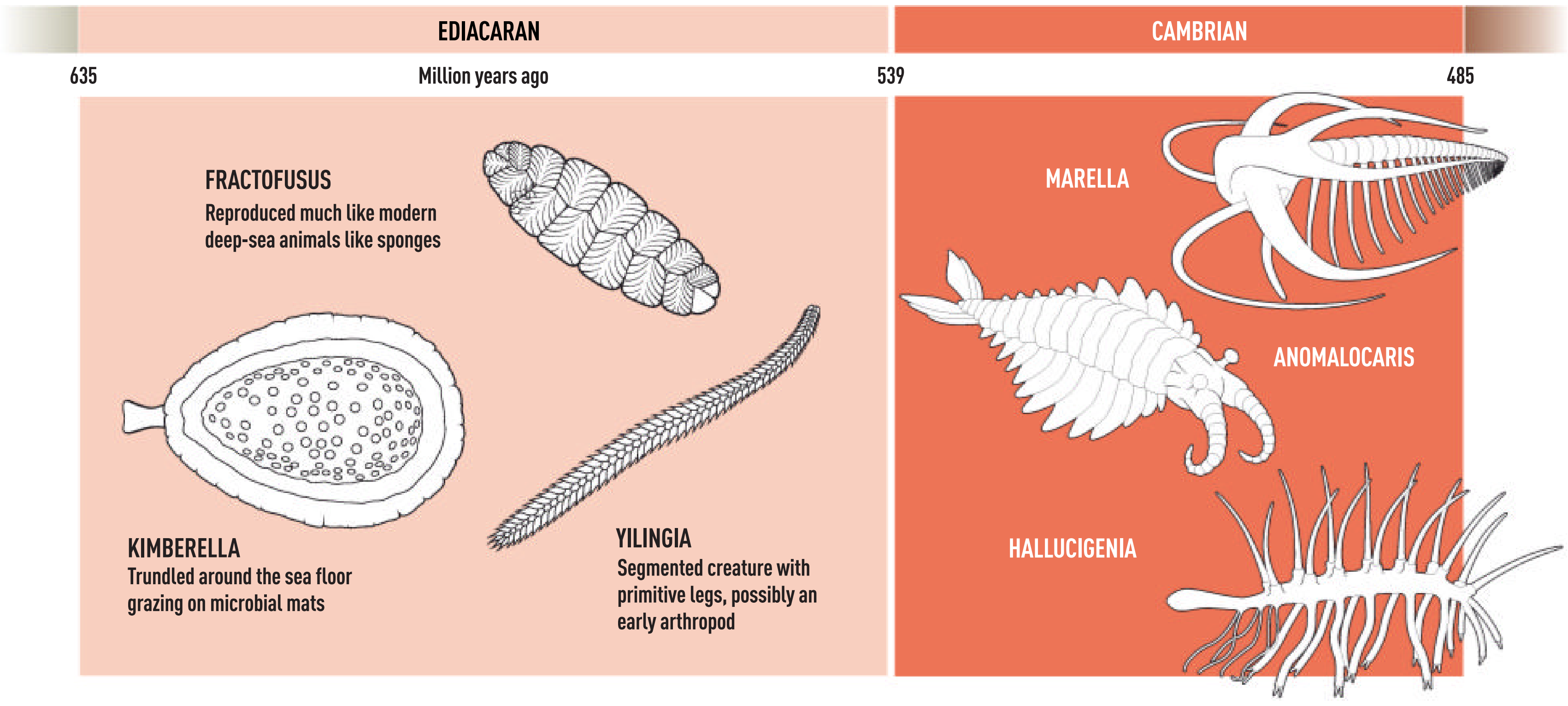
But the Cambrian explosion still seemed to mark the sudden blossoming of animal life. This remained the case even though geologists in the mid-20th century began finding fossils of large organisms, some a metre or more across, in rocks that predate the Cambrian explosion by 30 million years. These organisms were dubbed the Ediacaran biota because they date to the Ediacaran geological period, which precedes the Cambrian. But we couldn't quite figure out what to make of them.

←
Page 43 has more on Ediacaran finds

This wasn't only because none of these organisms seemed to possess obvious animal features like a gut or a mouth. Some, including those in a group called the rangeomorphs, also had a fractal anatomy dissimilar to animals, in which tiny parts of the organism looked like miniature versions of larger parts (see diagram, above).

The influential palaeontologist Adolf Seilacher argued that the Ediacaran organisms were so clearly unrelated to the animals of the Cambrian that they were effectively as strange to our modern eyes as life on another planet would be. Seilacher was one of many researchers who felt that Ediacaran species and ecology

We used to think that animals burst onto the scene in an abrupt "explosion" of complex life during the Cambrian Period. However, new discoveries are revealing animal-like creatures in the earlier Ediacaran Period


EDIACARAN
CAMBRIAN
635
Million years ago
539
485
FRACTOFUSUS
Reproduced much like modern deep-sea animals like sponges
KIMBERELLA
Trundled around the sea floor grazing on microbial mats
YILINGIA
Segmented creature with primitive legs, possibly an early arthropod
MARELLA
ANOMALOCARIS
HALLUCIGENIA

looked so alien that it was impossible to escape the conclusion that the Cambrian was indeed a dramatic explosion of familiar animal life.

In the past 10 years, however, geologists have shifted their thinking. Sophisticated analytical techniques have started to suggest that some of the weird species of the Ediacaran were animals after all, and that they behaved uncannily like modern creatures.

Perhaps the most compelling clues come from rocks in Newfoundland, Canada, that contain traces of the earliest Ediacaran communities. Here, you don't just stumble on the occasional nicely preserved specimen. You walk over bedrock exposures 120 square metres in area that each contain thousands of fossils.

Each giant slab is a Pompeii-like snapshot of the deep-sea floor community as it was 570 million years ago. Emily Mitchell at the University of Cambridge, UK, and her colleagues mapped the size and distribution of fossils of an oval-shaped rangeomorph called *Fractofusus*. This Ediacaran grew up to 40 centimetres in length and was covered in peculiar, fractally repeating pleats. The data, published in 2015, showed that the largest individuals were scattered randomly across the ancient sea floor, surrounded by halos of smaller and smaller individuals. This suggests that *Fractofusus* reproduced in a sophisticated way. It generated waterborne offspring that would drift and land on an empty bit of sea floor. Then, as the offspring developed into adults, each would form a series of tentacle-like fingers, the ends of which would then grow into a clone of the adult.

That is a little like how certain modern deep-sea animals such as sponges and corals reproduce, says Mitchell. *Fractofusus* may have had a fractal-like anatomy unlike that of any modern animal, but it apparently reproduced like some of today's animals do. That might hint that it was related to those animals, although Mitchell says we can't rule out the possibility that *Fractofusus* was instead related to fungi, which sometimes also reproduce this way.

In any case, it isn't just *Fractofusus* that behaved surprisingly like a modern animal. Another Ediacaran organism called *Kimberella* left behind tracks that suggest it trundled around, grazing on microbial mats on the sea floor, which is a strikingly animal-like way to behave. Simon Darroch at Vanderbilt University in Tennessee and his colleagues have used computer models to show that another Ediacaran, *Tribrachidium*, probably fed on suspended particles, just as many modern shellfish do. In a sense, it doesn't even matter whether these Ediacaran organisms were animals or not: they were behaving and reproducing like modern marine animals do, which suggests that Ediacaran ecology was more like today's than we previously thought.

There might also be good reason to believe that at least some strange Ediacaran organisms really were animals. The strongest evidence for this came in 2018. Ilya Bobrovskiy at the Australian National University in Canberra and his colleagues analysed the chemistry › of rocks containing an Ediacaran organism called *Dickinsonia*. The rock around the fossils had a chemical signature associated with algae, which would make sense because the shallow sea floor on which *Dickinsonia* lived was probably coated in mats of algae. But the molecules within the fossils themselves included a particular type of steroid that is produced only by animals, implying that *Dickinsonia* was an animal.

That isn't all. Palaeontologists have also begun to find evidence that the Ediacaran seas did contain animals that probably were related to modern ones. For instance, in 2017, Rachel Wood at the University of Edinburgh, UK and her colleagues announced they had found tiny fossils of what were previously assumed to be exclusively Cambrian animals in Siberian rocks dating to the final 10 million years of the Ediacaran. Tiny burrows that could have been produced by nematode-like worms have also been seen in Ediacaran rocks from Brazil dating back at least 550 million years.

That is an important discovery because nematodes, primitive though they may seem, are relatively advanced animals. One study even suggests that they are closely related to arthropods: animals like spiders and lobsters, with legs and an exoskeleton. If nematodes were around in the Ediacaran, it is plausible arthropods were too.

Indeed, in 2018, minuscule footprints left by an unidentified, multi-legged animal were reported, stretching several centimetres in rocks from south China thought to be up to 551 million years old. And in 2019, a team caught a rare glimpse of another possible early arthropod in the same rocks: a 25-centimetre-long segmented creature called *Yilingia* that seems to have had primitive legs.

It seems animals, both familiar and weird, really were thriving millions of years before 539 million years ago.

THE STORY OF PLANTS

Plants may not be as immediately exciting to watch as animals, but their story is just as epic. Billion-year-old fossil seaweeds found in China could be the ancestors of all land plants. The tiny seaweeds have branching structures and disc-shaped features to fix them to rocks, making them the oldest complex plants yet discovered.

These ancient organisms – named *Proterocladus antiquus* – would have grown on rocks in shallow seas. They appear to have had specialised cells for reproduction and for forming spore-like cells that would have remained dormant when conditions got tough and regrown later. The fossils are up to 3 millimetres in length, so the living plants would have been visible to the naked eye. They are very similar to some present-day green seaweeds.

Land plants came much later. It has been estimated that land plants first emerged 515 million years ago, but actual fossils are rare and not quite so old. Many botanists assume that the first land plants grew like mosses, and more complex plants like shrubs and trees evolved later. However, this isn't a settled question.

Furthermore, many familiar kinds of plant evolved surprisingly late. The most famous example is flowering plants. Today, flowering plants – known as angiosperms – are the most diverse group of land plants. The oldest angiosperm fossils so far found are 135 million years old, and many researchers believe this is when the group originated. The fossil record suggests the group then became diverse by 130 million years ago.

But how flowering plants became highly diverse so shortly after their emergence has long perplexed researchers, including Charles Darwin. The fossil record and genetics offer conflicting evidence, with the latter pointing to a much older origin.

HERVÉ SAUQUET & JÜRG SCHÖNENBERGER

The first flowering plants evolved just 135 million years ago

This revelation is so fresh that opinion is still divided on how to recast the rise of the animals. In 2019, a team including Wood and Mitchell argued that animals actually became dominant by diversifying through a series of relatively small evolutionary changes over tens of millions of years. As such, they concluded that it is debatable whether there really was any Cambrian explosion worthy of the name.

In contrast, Darroch still thinks there was a distinct evolutionary explosion, albeit one that began much earlier than we had thought. In a paper published in 2018, he and his colleagues argued that the explosion didn't take place 539 million years ago but 12 million years earlier, when the Ediacaran period was still in full swing. It is then that we see the first clear signs that tiny yet unmistakably modern animals were scuttling around in the shadow of the larger Ediacaran organisms.

If there was a distinct explosion, our chances of working out why it happened would be immeasurably improved if we could figure out when and where to look for clues. For comparison, by 54 million years ago, mammals were thriving across the world and the first primates had just appeared. But our explanations for this explosion of mammal life are lacking if they don't acknowledge the dinosaur-ending asteroid impact that had occurred 12 million years earlier.

As far as we know, there was no asteroid impact to trigger the evolutionary explosion 551 million years ago. But we do know that huge changes were afoot at the time. The problem is that they are frustratingly mysterious. Geochemists studying the chemical isotopes locked away in 551 million-year-old rocks have found signs of what they describe as the single biggest shift in the ratio of carbon-13 to carbon-12 in Earth's history. It is known as the Shuram event.

Carbon shifts often indicate ecosystems in flux. At other times in our planet's past, they have been linked to sudden drops in the quantity of nutrients generated through photosynthesis – and with mass extinction events. But the size of the carbon shift during the Shuram event is so large that it has so far defied explanation, even after 25 years of study. And deciphering the event has now taken on new significance, given the realisation that it might have been the trigger for the blossoming of animal life as we know it.

Some geologists argue that the Shuram event reflects what they describe as "turmoil" from dramatic changes to the paths that water took as it slowly circulated around the ancient oceans. Others suspect that it represents a huge global warming event that released carbon-containing methane into the oceans and atmosphere. Either of these environmental disturbances might somehow have triggered the dawn of modern ecosystems, but we still don't know quite how.

Alternatively, the Shuram event might reflect a sudden rise in atmospheric oxygen. Conventionally, a surge in oxygen levels has been viewed as a potential trigger for the sudden flourishing of animal life – although these days, many biologists suspect that the story is more complicated.

It is also exasperatingly unclear how animal life responded to the Shuram event. Geologists have struggled to find rocky outcrops that both record the Shuram geochemical signal and contain enough Ediacaran fossils to show how ecosystems reacted. Evidence from such sites might finally help explain when and why the most dramatic event in the history of life on Earth occurred – or it could indicate that the story of early animal life is so complex that there wasn't a neatly definable Cambrian explosion after all. ▮

ANAKESEENADEE/ISTOCK PHOTO

FROM SEA TO LAND AND AIR

Today, life is found virtually everywhere on Earth, from the deepest abysses of the ocean to the peaks of the highest mountains. This represents a triumph of evolution.

Reptiles, birds and mammals owe it all to a fish that left the sea

BY THE end of the Cambrian Period, animals and plants were still confined to the sea. Only microbes lived on the land and it took a long time for their larger cousins to join them.

Different groups moved onto the land at different times, so there was no single colonisation event. Plants seem to have reached the land first, with animals following later.

Insects probably led the way. The oldest insect fossil is some 410 million years old, but it is an elaborate creature, indicating that insects evolved much earlier. Their ancestors were once thought to be myriapods – land animals including millipedes and centipedes – but Björn Marcus von Reumont, an evolutionary biologist at the University of Giessen in Germany, and others had different ideas. In 2010, he published research suggesting that the closest living relatives of insects are aquatic crustaceans called remipedes. Similarities in their brains, their nervous systems and many of their proteins all point to an ancient common ancestor, he says. That would mean not just that insects evolved in the watery margins between sea and land, but also that they are much older than we thought.

In 2014, Bernhard Misof at the Zoological Research Museum Alexander Koenig in Bonn, Germany, and his colleagues carried out a huge genetic study of insect evolution and relatedness. This confirmed their watery origins. “Insects are terrestrial crustaceans,” says Misof. And they evolved about 480 million years

"Insects probably evolved in the watery margins between sea and land"

ago, the study suggests, making them among the first things ever to walk on land.

Insects were also the first to evolve powered flight. In the rolling hills around the village of Rhynie in Aberdeenshire, UK, the rocks are teeming with fossils of tiny centipedes, mites, spiders and stubby plants, all petrified in the silica-rich waters of a volcanic hot spring around 410 million years ago.

But in 2004, Michael Engel at the University of Kansas in Lawrence found something else. Examining one of the fossils under a microscope, he was gobsmacked to see tiny, perfectly preserved mouthparts of a type only found in insects, and not just any kind of insect. "This was our first peek at a flying insect," he says. Although its wings weren't preserved, all the evidence indicated that *Rhyniognatha hirsti* was a relatively advanced flyer. This would make the origins of flight even earlier, perhaps at the species explosion 440 million years ago.

What got insects into the air? Engel suspects they were climbing the stems of plants bordering swamps to feast on spores, and found it easier to glide back down. Silverfish – primitive flightless insects living today – have a tiny pair of flat lobes extending out of their thorax, which they use for control when falling. And genetic analysis suggests wings evolved by the expansion of such lobes along with the development of hinges derived from the legs to control movement.

When most of us think about the colonisation of the land, however, we are thinking of the tetrapods: backboned animals with four limbs. Tetrapods evolved from fish and eventually gave rise to all amphibians, reptiles, birds and mammals.

So far, we have uncovered a number of flagstones on this evolutionary path. In rocks dating from 375 million years ago, the end of the Devonian Period, palaeontologists have found a fossilised shoal of fishy creatures that document the evolution of fins into the limbs and fingers that would eventually carry them onto land. Fleshy-finned fish related to today's lungfish mark the start of the transition, with fossils like *Panderichthys* from Latvia and the 375 million-year-old *Tiktaalik* from Ellesmere Island, Canada, demonstrating how fin bones were modified into the rudiments of our own appendages.

Fast forward about 10 million years and vertebrates seem even better suited to wandering ashore. There was *Acanthostega*, roughly salamander-shaped and 60 centimetres long, with well-defined limbs and eight fingers on each hand, and the larger *Ichthyostega*, with its seven digits. Although recent studies suggest it would have been more comfortable in water, *Ichthyostega* was capable of dragging its body along the mud banks. At this point, early tetrapods had limbs, fingers and the ability to breathe air, inherited from their lungfish-like ancestors.

The next group to evolve powered flight were the pterosaurs: flying reptiles that lived alongside dinosaurs. Birds came later, evolving from theropod dinosaurs. Flying mammals seem to have evolved only after the meteorite impact that wiped out non-avian dinosaurs. ▮

Spinosaurus is the only known dinosaur adapted to aquatic life

RISE OF THE DINOSAURS

The Mesozoic Era between 252 million and 66 million years ago was the age of dinosaurs, pterosaurs, giant marine reptiles and much more. Here are three of the most extraordinary.

SPINOSAURUS

LOOK at the jaws of *Spinosaurus* and you might conclude it was like a crocodile. Examine its gigantic claws and it is like a bear. Its broad, flat toe bones are like those of a wading bird. What could the life of a creature with such apparently conflicting features have been like? Making sense of this fantastic beast would pay dividends, because *Spinosaurus* might explain one of the biggest mysteries of dinosaur evolution.

Everyone agrees that *Spinosaurus* was a giant. We don't have a complete skeleton, but estimates suggest it was about 15 metres long, making it the largest carnivorous dinosaur yet found.

It belonged to a dinosaur family called the spinosaurids that appeared roughly 150 million years ago. These animals had crocodile-like jaws and teeth, but lacked the sail that *Spinosaurus* itself had. And like many crocodiles, they probably ate fish. A spinosaurid fossil discovered 35 years ago in the UK even had partially digested scales in the space where its stomach had been. Fish was on the menu for many of the creatures that shared the world with dinosaurs, including the reptilian ichthyosaurs and plesiosaurs that patrolled the seas. But spinosaurids are the only large dinosaurs known to have eaten fish.

Huge jaws are the only tool a crocodile needs to catch prey, but spinosaurids also had formidable claws that were at least 30 centimetres long. They have been compared to the huge claws grizzly bears use to hook fish out of streams. But in 2017, David Hone at Queen Mary University of London and Thomas Holtz at the University of Maryland in College Park pointed out that the animals couldn't see their claws, which makes them an unlikely precision hunting tool. Maybe the claws were actually used to dig up burrowing prey, says Hone. No one knows.

Spinosaurus arrived into this dinosaur family about 100 million years ago. The most complete skeleton of the animal was discovered in Morocco in 2008 by local fossil hunters who sold their find to rich collectors. It ended up at the Milan Natural History Museum in Italy. Nizar Ibrahim at the University of Detroit Mercy in Michigan realised how important the specimen was

and tracked down the site where it had been unearthed.

A description of the specimen published in 2014 caused a stir by suggesting *Spinosaurus* was weird, even for a spinosaurid. Ibrahim's team reported that the animal's torso was long, its hips were weak and its hind legs were short. What is more, it had feet like a modern web-footed shorebird, with long toe bones that had flat undersides. No other spinosaurid we know of had feet like that.

These aren't the features of a dinosaur that chases down prey on land. Ibrahim argued that they indicate an animal in the early stages of an evolutionary transition from land to water. The team pointed to similar features in the ancient four-legged ancestors of whales, which independently evolved 50 million years ago when they were still living by rivers. Like those early "walking whales", *Spinosaurus* had unusually thick-walled and dense leg bones, a feature believed to reduce buoyancy and allow animals to move around more easily in water.

Nevertheless, there is debate about how comfortable *Spinosaurus* was in water. The most dramatic of the animal's features are the 1.7-metre-tall bony spines projecting vertically up from its backbone. They look a lot like the spines inside a bison's fatty hump, and 20 years ago some researchers argued that *Spinosaurus*, too, had a fatty hump. Today, the consensus is that the bones supported a sail, probably used for social or sexual display.

Either way, the bony spines put a limit on *Spinosaurus*'s swimming ambitions. One consequence is that the animal would have been prone to overturning when swimming.

Yet even if *Spinosaurus* was a terrible swimmer, its dense leg bones and shorebird-like feet suggest that it spent a large chunk of its life wading and feeding in shallow water.

And therein lies the mystery. Dinosaurs dominated Earth for 135 million years, but *Spinosaurus* is almost the only one known to have evolved adaptations for aquatic life. That means we have the debate back to front: the oddity isn't *Spinosaurus*'s features, but that water-loving dinosaurs were so rare. Whatever was going on, *Spinosaurus* was evolution's best attempt to turn a dinosaur into a sea monster – but for one reason or other, it was doomed.

WALBYENT/ISTOCK PHOTO

PATAGOTITAN

For a century, visitors to the Field Museum in Chicago, Illinois, have marvelled at a display featuring two African bush elephants, frozen mid-fight. In the past couple of years, however, this awesome spectacle of the largest living land animals has been overshadowed by an enormous skeleton. As impressive as the elephants are, they look like squabbling children beside *Patagotitan*, a 100-million-year-old sauropod dinosaur that was as long as a blue whale, taller than a giraffe and probably outweighed each elephant 10 times over.

Since 2014, when news first broke of its discovery, *Patagotitan* has frequently been described as the most massive animal ever to walk the Earth. Such superlatives captivate us. Even if you aren't a dinosaur fan, it is awe-inspiring to think that the skeleton in the Field Museum belongs to a creature that is as big as they get.

Except it isn't. Weighing up such giants isn't simple, but new calculations indicate that other dinosaurs from the same family – the aptly named titanosaurs – were at least as massive. In fact, *Patagotitan* might not even come close to claiming the heavyweight title. Some palaeontologists now believe that the ground once trembled under the mass of a near-mythical dinosaur that was twice as heavy as *Patagotitan*.

Way back in 1878, Philadelphia-based palaeontologist Edward Cope received delivery of a fossil from a quarry in Colorado. It was part of a sauropod vertebra – a spine bone – and it was astonishingly large: the fragment alone was 1.5 metres tall. Cope named the dinosaur *Amphicoelias fragillimus*. He then, somehow, misplaced the fossil, or perhaps it was so fragile – as the name suggests – that it crumbled to dust. Ever since, *A. fragillimus* has been considered almost legendary. Some simply refuse to accept that the bone was as large as Cope claimed, because that would make the dinosaur unfeasibly huge.

It has been estimated that the complete vertebra stood at 2.4 metres tall. The equivalent bone in *Patagotitan* is 1.4 metres tall. This has led to estimates of the animal's body mass at between 80 and 120 tonnes, making it about twice as heavy as *Patagotitan*. Unfortunately, without discovering many more fossils, we can't be sure just how big the biggest ever land animals were – however frustrating that might be to some museum-goers.

Patagotitan might be the largest dinosaur – or perhaps nowhere near

ARCHAEOPTERYX

The discovery of *Archaeopteryx*, a few years after the publication of *On the Origin of Species*, couldn't have been better timed. Charles Darwin's theory of evolution by natural selection predicted that the fossil record should be full of transitional forms, as one species gradually evolved into another. Yet these missing links were, well, missing. Then, this strange bird-like dinosaur was unearthed – and instantly became a poster child for evolution.

After all this time, you might think there is little left to discover about the "first bird". In fact, much of its story has yet to be told. Only in 2019 did it emerge that the original *Archaeopteryx* fossil – a feather – wasn't what it seemed. And in recent years, we have found other contenders for the title of first bird. Nevertheless, new insights into the origins and lifestyle of *Archaeopteryx* reveal it to be a real trailblazer, making an epic journey over sea before settling on remote islands – a trip that shaped its evolution in a way that certainly would have intrigued Darwin.

The first *Archaeopteryx* skeleton was found in Germany in 1861, close to – and shortly after – the feather. It was about the size of a crow, and headless. Only with the discovery of a second skeleton a decade later did it become clear that instead of a bird-like beak, *Archaeopteryx* had a snout filled with teeth. Eleven specimens have been found in total, although one vanished mysteriously in 1991 after the death of its owner. Those that remain reveal an animal that lived about 150 million years ago in what is now western Europe.

Other bird-like dinosaurs lived in China, according to fossils unearthed since the 1990s. Like *Archaeopteryx* and modern birds, they are theropods, a group of dinosaurs with hollow bones and three-toed limbs that include tyrannosaurs and velociraptors. The oldest of the Chinese fossils date from 160 million years ago, and reveal an animal that had feathers but probably couldn't fly. The first creatures that closely resemble modern birds – theropods capable of flight and with beaks – date from around 125 million years ago.

So *Archaeopteryx* was just one of several early bird-like dinosaurs. But details of its story are still emerging, and they shed new light on its evolution.

To understand how, we must travel back 175 million years to when the supercontinent Pangaea began to break apart. An ocean called the Tethys pushed in from the east, creating Laurasia in the north – a combination of what are now North America, Europe and Asia – and Gondwana in the south. Much of Europe was flooded, forming an inland sea with a couple of Madagascar-sized islands in the east and smaller ones further west. These remote western islands, known as the Solnhofen archipelago, are where *Archaeopteryx* lived.

The islands were tropical, lying 500 kilometres from the equator, and were surrounded by coral reefs. Artists' impressions often show *Archaeopteryx* flapping from tree to tree, but that is probably wrong, says Oliver Rauhut at the Bavarian State Collections of Palaeontology and Geology in Germany. "There's a complete lack of any evidence for large tree," he says. Instead, small shrubs appear to have dominated. Also, the very idea that *Archaeopteryx* could fly has been controversial. It may have been bird-like with feathers, but it lacked key markers of flight, such as a solid breastbone to anchor its wings.

Archaeopteryx was just one of several early birdlike dinosaurs

Determined to resolve the debate, in 2011, Ryan Carney at the University of South Florida in Tampa carried out a microscopic examination of an *Archaeopteryx* feather. This revealed pigmented structures called melanosomes indicating that the plumage was matt black, which would have aided flight. "In modern birds, black melanin pigment substantially increases the strength and durability of feathers," says Carney. Unfortunately, his finding didn't settle the matter: the feather he scrutinised was the original *Archaeopteryx* fossil, which, according to a recent analysis, probably belonged to another dinosaur. Evidence Carney has gathered since, however, makes a strong case. Unlike other studies, which tend to focus on a single anatomical feature, he looked at the bigger picture, such as how the muscles and joints moved the entire forelimb. Based on this analysis, in 2016, Carney concluded that *Archaeopteryx* could fly.

This fits with what Rauhut and his colleagues have reported as well. Examining the eleventh specimen, they found that its body was covered in pennaceous feathers, the kind that in modern birds have evolved for flight. Their shape indicated that this process had already begun in *Archaeopteryx*. But it probably wasn't a very adept flier. In 2018, another group compared the internal structure of *Archaeopteryx* bones with those of modern birds and concluded that it was able to fly, but only for short bursts, like a pheasant.

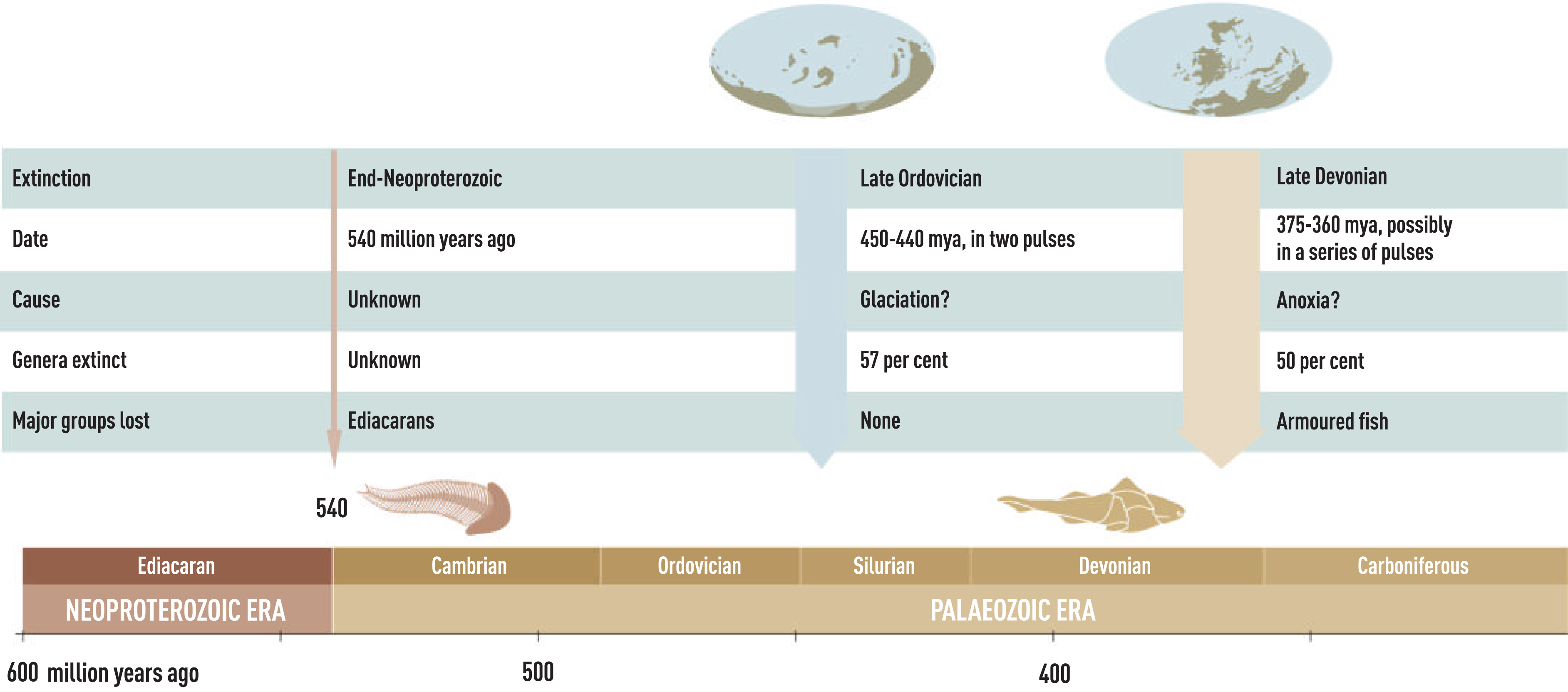
Not glamorous, but it was enough to make an epic journey. In a 2017 paper, Rauhut argued that bird-like dinosaurs evolved on the Asian part of Laurasia then migrated west towards what is now Europe. *Archaeopteryx* alone appears to have crossed the inland sea to reach the Solnhofen archipelago.

Flight may have helped *Archaeopteryx* evade predators, but it is unlikely to have been skilled enough to catch its own prey on the wing. We know it hunted by day, however, because it lacks the large eye sockets found in nocturnal animals. But what did it eat? The shape of its teeth suggests insects. Rauhut notes that each *Archaeopteryx* specimen has distinctive teeth, hinting that they were adapted for different diets depending on what was available on the island where it lived. For instance, the eighth has large, cone-shaped back teeth, suitable for cracking hard foods. This hints that it ate insects with tough shells, perhaps beetles.

It isn't just their teeth that differ. The bones in each *Archaeopteryx* skeleton also vary in size and proportions, raising questions about whether they really are all from the same species, as some research has concluded. Other work has grouped them into at least two species: *Archaeopteryx lithographica* and *Archaeopteryx siemensii*. And a paper on the eighth specimen published in 2018 suggested it belonged to a new species.

All of this controversy over classification has an intriguing implication. It suggests a parallel between *Archaeopteryx* and the Galapagos finches studied by Darwin. These birds also live on remote islands and are adapted to the different opportunities offered by their particular island habitat. Thought to number 17 species, they are a classic example of adaptive radiation, where a multitude of species evolves rapidly from a single one. *Archaeopteryx* may have done the same thing on the Solnhofen archipelago. Perhaps they are the Darwin's finches of the Jurassic. ∎

JOSE ANTONIO PENAS/STOCKTREK IMAGES/ALAMY LEONELLO/ISTOCK



Extinction	End-Neoproterozoic	Late Ordovician	Late Devonian
Date	540 million years ago	450-440 mya, in two pulses	375-360 mya, possibly in a series of pulses
Cause	Unknown	Glaciation?	Anoxia?
Genera extinct	Unknown	57 per cent	50 per cent
Major groups lost	Ediacarans	None	Armoured fish

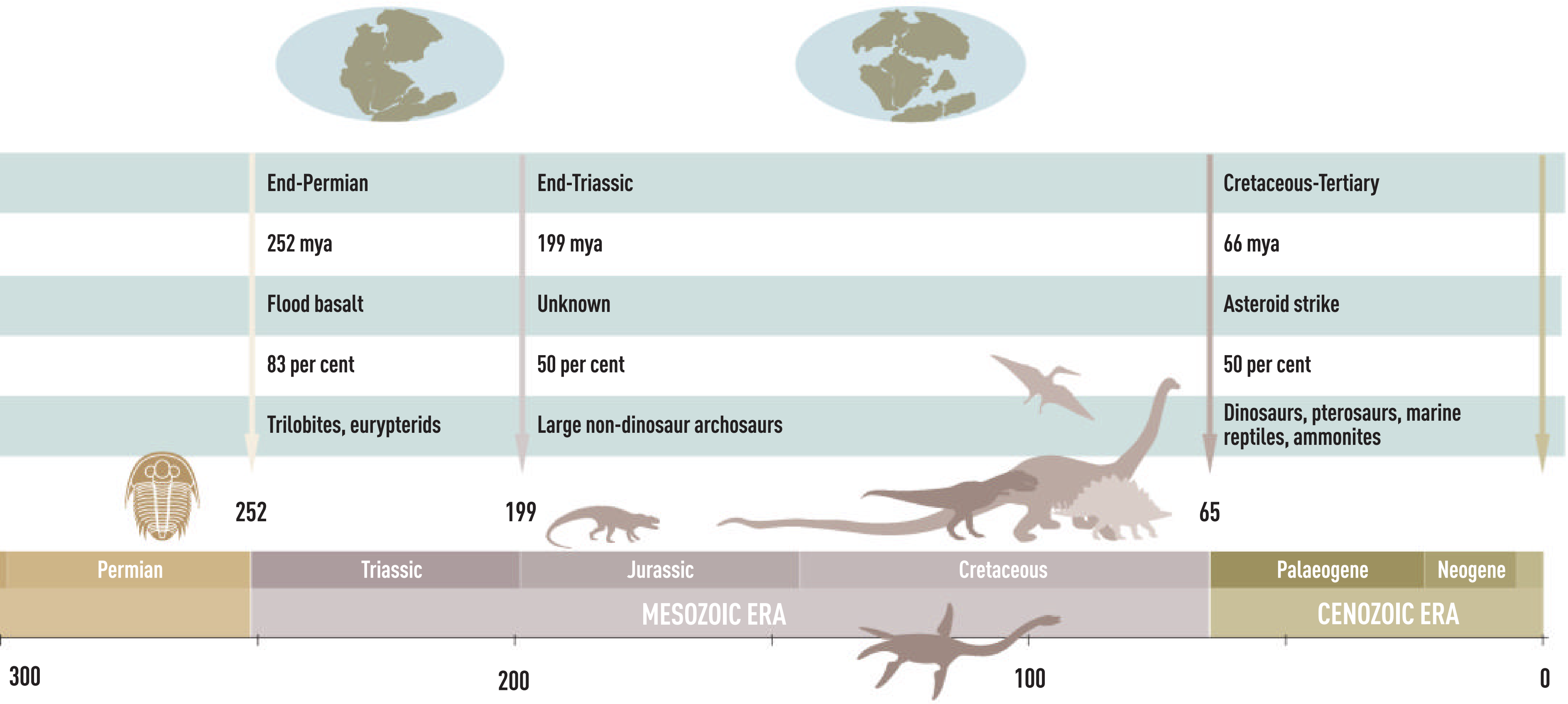
MASS EXTINCTIONS

Every now and again, life on Earth faces a crisis. While the demise of the dinosaurs is the most notorious, at least five times in the past 540 million years, half or more of all species have been wiped out in a short period. These mass extinctions are important punctuation marks in the history of life, as once-dominant groups are swept away and replaced with new ones.

GIVEN how important we now know mass extinctions are to understanding the history of life, it may seem surprising that no one was much interested in the idea until the 1970s. Of course, the great Victorian palaeontologists, such as Richard Owen and Thomas Huxley, were aware that dinosaurs and other ancient creatures were extinct, but they didn't see any role for sudden, dramatic events. Following Charles Darwin, they argued that extinction was a normal process: species originated at some point by splitting from existing species, and at some point they died out.

Extinction certainly is a normal part of evolution. Species come and go continually – around 99.9 per cent of all those that have ever existed are now extinct. The cause is usually local. For example, a lake might dry up, an island might sink beneath the waves or an invasive species might outcompete another. This normal loss of species through time is known as the background rate of extinction. It is estimated to be around one extinction per million species per year, though it varies widely from group to group. The vast majority of species meet their end in this way.

But sometimes many species disappear together in a short time. At the end of the last glacial period 11,000 years ago, for example, mammoths, woolly rhinos, cave bears and other large mammals adapted to cold conditions died out across Europe and North America. There have been many such "extinction events" through the history of life. But occasionally, extinction events are global in scale, with many species of all ecological types – plants and animals, marine and



terrestrial – dying out in a relatively short time all over the world. This is a mass extinction.

There is no exact definition of a mass extinction. The loss of 40 to 50 per cent of species is about the norm, but this is only the upper end of a spectrum of extinction events. We now recognise that there have been several mass extinctions over the past 600 million years – the period over which macroscopic life has existed in relative abundance. The first of these was about 540 million years ago, at the end of the Neoproterozoic Era (see diagram, above), when the enigmatic Ediacaran animals disappeared. Some palaeontologists also identify the late Cambrian as another time of mass extinction.

Three further mass extinctions punctuate the Palaeozoic Era. The late Ordovician, between 450 million and 440 million years ago, saw substantial losses among the dominant animals of the time: trilobites, brachiopods, corals and graptolites. The late Devonian mass extinction, beginning around 375 million years ago, was another long and drawn-out affair. Armoured fish known as placoderms and ostracoderms disappeared, and corals, trilobites and brachiopods suffered heavy losses.

The Palaeozoic ended with the enormous end-Permian mass extinction, possibly caused by a series of massive volcanic eruptions in present-day Siberia, which was associated with a loss of 80 to 90 per cent of species in the sea and on land. Several major groups disappeared, including trilobites and giant sea scorpions called eurypterids. The vast scale of the extinction is shown by the fact that two major structural ecosystems disappeared – reefs and forests. Nothing like that has happened in any of the other mass extinctions. It took 15 million years for new groups of coral to evolve and build reefs once more.

Another 50 million years or so passed before the next mass extinction, at the end of the Triassic. Fish, molluscs, brachiopods and other marine groups saw substantial losses, while extinctions on land opened the way for the dinosaurs. They dominated for 135 million years before being wiped out in the most recent extinction, the Cretaceous-Tertiary event.

Up to the 1970s, the best evidence suggested that the dinosaurs – along with pterosaurs, mosasaurs, plesiosaurs, pliosaurs, ammonites and many other groups – declined slowly over some 10 million years as a result of cooling climates. But though the hypothesis remains hotly disputed in some quarters, it now seems overwhelmingly likely that the cause was a massive impact from an asteroid that struck Earth just off the coast of present-day Mexico some 66 million years ago.

It sent up a vast cloud of dust that encircled the globe, blacking out the sun, preventing photosynthesis and so causing massive loss of life. As with previous extinctions, however, some life's misfortune was other life's good fortune – clearing the dinosaurs out of the way paved the way for the latest mammal-dominated era of life's history on Earth. ▮

Science fiction? No, it actually happened. Between 20 million and 7 million years ago, Earth really was dominated by apes. At least 100 species roamed the world before some of them evolved into humans – while others gave rise to modern apes like chimpanzees and gorillas.

PLANET OF THE APES

THE fossil record indicates that apes started out in Africa about 26 million years ago, and were firmly settled there 4 million years or so later in the form of *Proconsul africanus*. A close relative that lived 18 million years ago paints an extraordinary picture of these early apes. Remains of *Ekembo* were found preserved, Pompeii-like, in layers of volcanic ash on Rusinga Island, Kenya. What we have is an animal with arms and legs of equal length, a horizontally oriented backbone and a brain about the size of a modern baboon's. In other words, *Ekembo* looks like a largish monkey, but with a key difference – no tail. Tails allow many monkeys to balance, but *Ekembo* compensated with more limber wrists and hips and more powerful hands and feet for grasping. This set apes on a different path from Old World monkeys.

A second momentous change arose in a contemporary of *Ekembo*, called *Afropithecus*. The two look remarkably similar from the neck down, but have quite different jaws and teeth. Those of *Afropithecus* are far more robust, adapted for powerful crushing and grinding. Equipped like this, it could extract nutrients from foods with husks and shells impenetrable to the more slender jaws of *Ekembo*. It may not sound too impressive, but this ability had huge repercussions for

Chimps are among the descendants of the planet of the apes

ANDYWORKS/ISTOCK PHOTO

apes. With the capacity to eat a wider variety of foods, they could expand their range out of Africa and into Europe and Asia.

The oldest apes we know of in Europe belong to the genus *Griphopithecus* and date from 17.5 million years ago. They inherited the powerful bite of *Afropithecus*, but their teeth were a little different, more like those of our earliest direct ancestors in Africa. According to the fossil record, griphopiths were living in parts of what are now Germany and Turkey about 17 million years ago. At this time, much of Europe was in a subtropical zone. Seasonality was low and the climate was suitable for animals, like apes, that rely on a continuous year-round supply of fruit. However, as griphopiths migrated north, conditions would have proved more challenging – ultimately driving them to evolve new adaptations.

As well as moving northwards, griphopiths returned south, so that by some 15 million years ago, their range covered an area from Europe to East Africa. One member of the family, *Nacholapithecus,* living in Kenya around this time had evolved limbs with larger elbows and wrists, perhaps anticipating the development of the longer arms found in living apes and the earliest humans. However, griphopiths seem to die out in Africa, though we don't know why. The fossil record indicates that between 14 million and 8 million years ago, apes were a rarity there, and most were from ancient lineages related to *Ekembo* and bound for extinction.

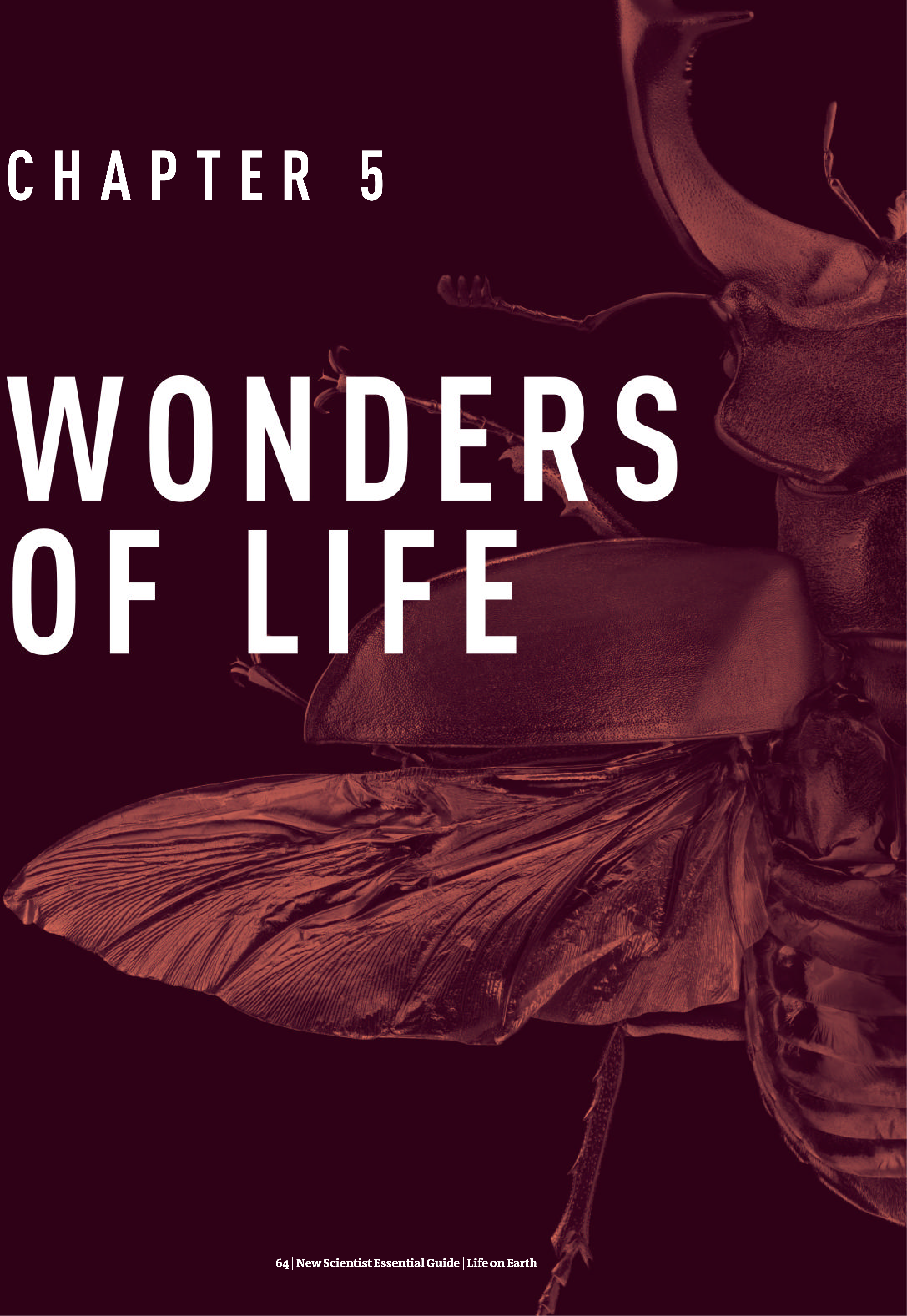
By contrast, in Europe, truly modern-looking great apes were emerging. Around 12.5 million years ago, the first ape with a more upright posture appeared. *Pierolapithecus*, sometimes called *Dryopithecus*, was unearthed in Catalonia, northern Spain.

The partial skeleton has a more vertical backbone, a broad chest, arms longer than legs, very mobile wrists and long, curved, powerfully grasping fingers. These features made *Dryopithecus* look more like today's great apes. They also indicate a major transition from walking like a monkey on all fours to ape-like movement, hanging and swinging below branches.

Hispanopithecus, living in what is now Catalonia a few million years later, had longer arms and an even more upright back. So did *Rudapithecus*, its contemporary in what is now Hungary. More significantly, to our knowledge, *Rudapithecus* is the first ape to evolve two other key features of modern great apes – a big brain and extended childhood.

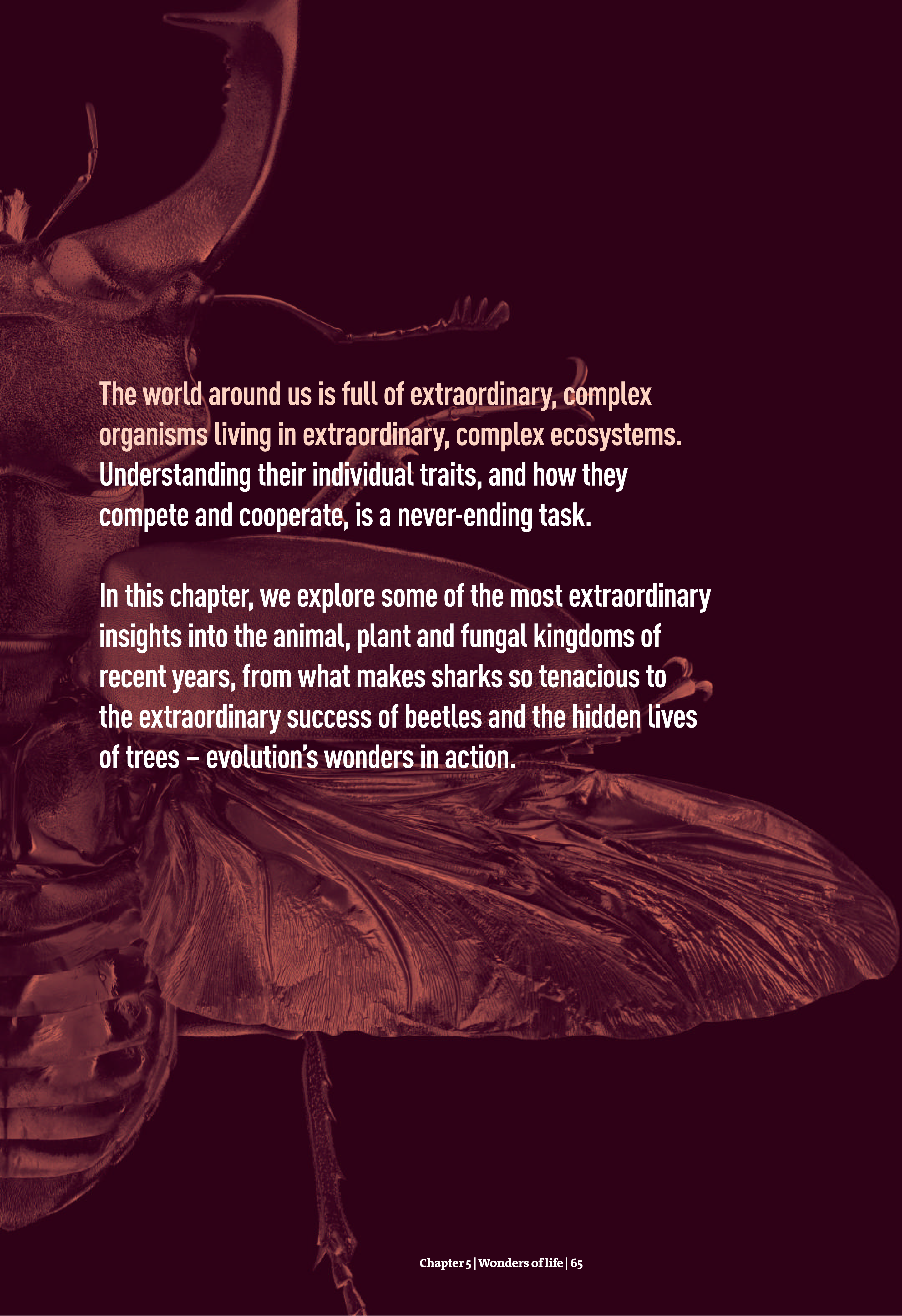
Gradually, conditions in Europe became too tough for apes, and about 10 million years ago they quit the continent for Africa.

There, the separate lines of our closest living relatives evolved, the gorillas branching off first and then chimps and humans veering apart. From our perspective, it is perhaps the last great diversion of lineages on the long path to the planet dominated by just one sort of ape today. ▮



CHAPTER 5

WONDERS OF LIFE



The world around us is full of extraordinary, complex organisms living in extraordinary, complex ecosystems. Understanding their individual traits, and how they compete and cooperate, is a never-ending task.

In this chapter, we explore some of the most extraordinary insights into the animal, plant and fungal kingdoms of recent years, from what makes sharks so tenacious to the extraordinary success of beetles and the hidden lives of trees – evolution's wonders in action.

THE SECRETS OF SHARK SUCCESS

Sharks are awe-inspiring, but also tenacious. As a group, they have been around for at least 420 million years, surviving four of the "big five" mass extinctions. That makes them older than humanity, older than Mount Everest, older than dinosaurs and older even than trees.

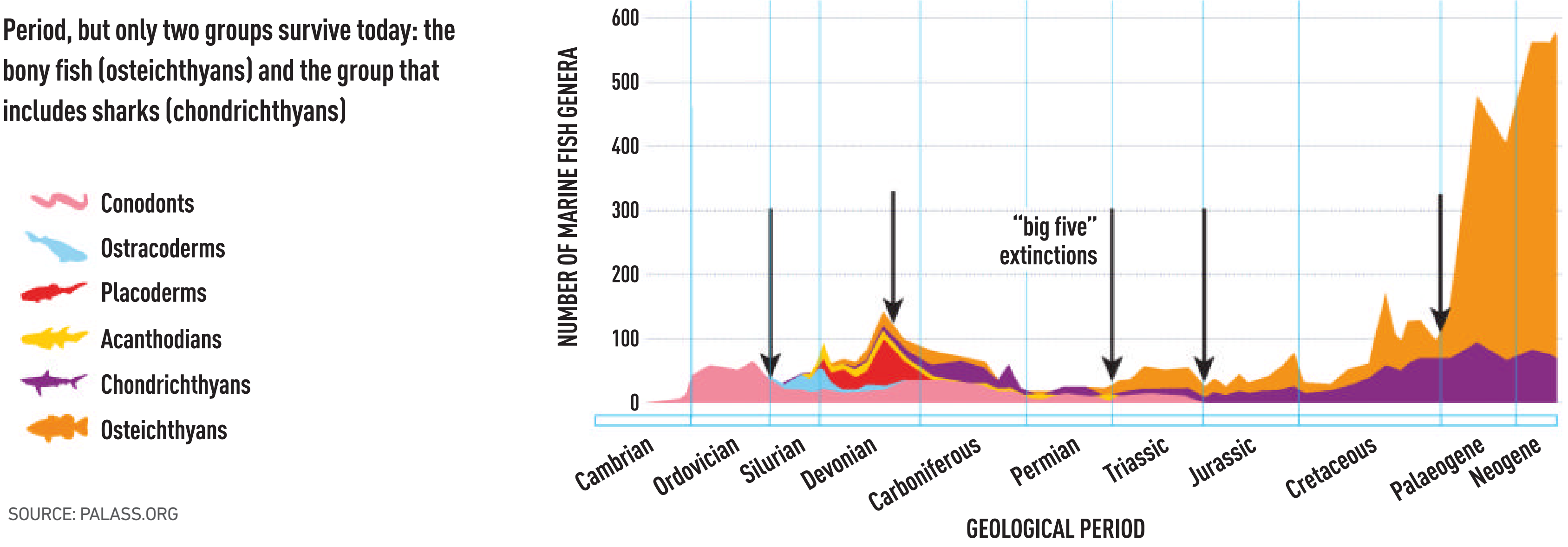
SHARKS, along with rays, skates and chimaeras, make up a group of fish known as Chondrichthyes, characterised by a cartilaginous skeleton. Fossil scales found in Siberia indicate that sharks originated in the Silurian Period, which began about 440 million years ago. It was a time when the world was warm, sea levels were high and corals reefs were starting to appear. Since then, thousands of shark species have existed, culminating in a golden age about 360 million years ago when they dominated the oceans, taking many weird and wonderful forms. Today, there are more than 450 shark species, ranging from well-known ones such as great whites and hammerheads to the exotic and bizarre, including goblin sharks, cookiecutter sharks and Japanese wobbegong.

Of course, many shark species are now extinct, but that is to be expected. It is estimated that extinction has been the fate of more than 99 per cent of all plants and animals that have ever lived. The puzzle instead is how sharks as a group have survived for so long.

← Turn back to page 60 for more on mass extinctions

Palaeoecologist Sora Kim at the University of California, Merced, who studies ancient and modern sharks, sees one clue in their faeces. "When a shark poops, there's hardly any solids," she says. "It's more of a clearish goo." This indicates that they possess a highly efficient digestive system able to process almost all of ›

LINDSAY_IMAGERY/ISTOCK
PREVIOUS PAGE: CONSTANTIN CORNEL/ISTOCK



Marine fish first evolved in the Cambrian Period, but only two groups survive today: the bony fish (osteichthyans) and the group that includes sharks (chondrichthyans)

SOURCE: PALASS.ORG

what they eat. That can be helpful if food gets scarce, says Kim, which is likely to happen during a mass extinction event. Earth's third and biggest mass extinction, for example, which happened about 252 million years ago, saw upwards of 96 per cent of all marine life disappear.

As well as letting very few nutrients go to waste, sharks are also surprisingly unfussy eaters. A few years ago, Kim and her colleagues studied the diet of great white sharks by analysing chemical signatures in their backbones. "Even though we think of them as being apex predators at the top of the food chain, they definitely aren't that all of the time," says Kim. It isn't all seals, sea lions and squid, in other words. In fact, research published in 2018 revealed that one shark species, the bonnethead, is omnivorous, consuming copious amounts of seagrass along with shellfish. Such dietary flexibility would have worked in sharks' favour when the going got tough.

More evidence of shark adaptability comes from their teeth. Unlike their cartilaginous skeleton, their teeth are extremely hard, which gives them a good chance of being preserved in the fossil record. In Canada's Northwest Territories, teeth belonging to sand tiger sharks litter ancient sediments near the Muskox and Eames rivers. They are between 53 million and 38 million years old, dating from the Eocene, an epoch when Earth was about 9°C to 14°C warmer than it is today and ocean water less salty as ice caps melted into them. Here, too, sharks seem to have done just fine.

Other shark species seem to positively relish being in hot water. When ocean engineer Brennan Phillips at the University of Rhode Island explored the Kavachi submarine volcano off the Solomon Islands, he didn't expect to find sharks: the water from hydrothermal vents can exceed 400°C. Yet swimming through the murky depths, his team spotted hammerhead and silky sharks there. Submarine volcanoes have been relatively constant features in the oceans since long before sharks evolved, he says. If today's sharks are at home here, their ancestors might have been able to rely on volcanoes as other habitats came and went.

Mass extinctions will have put paid to many other species of shark, and reshuffled the list of those around. In fact, the first such event that sharks lived through left the group with its most notable characteristic. This was Earth's second mass extinction, which began about 375 million years ago, probably driven in part by massive glaciations. Before this cataclysmic event, sharks mostly had bony skeletons, says Lauren Sallan at the University of Pennsylvania. Afterwards, most had soft, cartilaginous skeletons, just as they do today. What's more, post-extinction sharks were tiny – usually less than 10 centimetres long.

The second extinction changed the world, and sharks changed with it. Still, they had traits that enabled the group as a whole to weave through the cataclysm. And their flexibility means that they remain resilient. "People ask me: 'Does climate change affect sharks?'" says arine biologist and consultant David Shiffman. "The short answer is: 'For the most part, not really.'" But there is one thing sharks can't easily swim away from – us.

Overfishing is the main risk sharks currently face. As a group, they possess special powers that have made them extinction proof, but today about 16 per cent of shark species are listed by the International Union for Conservation of Nature as threatened. If humans are turning sharks into shark fin soup faster than the animals can reproduce, their days may finally be numbered. ▮

Once defamed as slow and stupid, sloths are now recognised as masterworks of mammalian evolution – and we could all learn from their energy-saving tricks.

LIFE IN THE SLOTH LANE

Sloths' exquisite adaptations have allowed them to survive for 30 million years

JONATHAN ROSS/ISTOCK PHOTO

GEORGES-LOUIS LECLERC, the Comte de Buffon, was the most famous naturalist on the planet in the middle of the 18th century, and he didn't think much of the New World. He proclaimed the Americas "degenerate", a sodden, miserable land filled with weak and inferior species. But Buffon reserved his most biting contempt for one creature in particular.

He wrote of their "too short" and "badly terminated" legs, of their "slowness, stupidity… and even habitual sadness". "These sloths," he continued, "are the lowest term of existence in the order of animals with flesh and blood. One more defect would have made their existence impossible."

Buffon couldn't have been more wrong. What he saw as shortcomings we now realise are exquisite adaptations that have allowed sloths to thrive in an exceedingly austere niche for at least 30 million years. In fact, the closer we look at sloth biology, the more we see just how hard evolution has had to work so that these notorious dawdlers can take it easy.

One reason we know so little about sloths is that they are surprisingly difficult to study. They live high in the canopies of South and Central America and are extremely hard to spot: they are small, they rarely move and their fur often gets matted with green algae, making them blend in with the leaves.

To figure out exactly how slow they are, in 2014, Jonathan Pauli at the University of Wisconsin-Madison and his colleagues went to Costa Rica to measure the metabolic rates of three-toed brown-throated sloths and Hoffmann's two-toed sloths. They found that while both species have extremely slow metabolisms, the three-toed sloth is a record-breaker. The rate at which it expends energy in the wild, known as the field metabolic rate, came in at 162 kilojoules per day per kilogram, meaning it has lower energy needs than any other mammal that isn't hibernating, including renowned slouches like koalas (410 kJ/day/kg) and giant pandas (185 kJ/day/kg).

Part of the reason sloths are such extreme energy savers is their diet. They are arboreal folivores, meaning they live in trees and eat leaves. It is a deeply unpopular lifestyle choice, occurring in just 0.2 per cent of mammal species, and for good reason: leaves tend to be rather difficult to digest and contain few nutrients. Some tree-living leaf-eaters, such as howler monkeys, get around this by gorging on massive quantities of the stuff.

Sloths have adopted a different strategy: they nibble a bit here and there, making sure to keep their stomachs full. And they don't rush digestion. It can take anywhere from two days to nearly two months before swallowed food emerges again as dung, which makes this the longest digestive process on record for a plant-eating mammal. That is particularly weird when you consider that among mammals, the digestion rate typically depends on body size, with big animals taking longer to digest their food.

A long and winding alimentary canal isn't the only way sloths conserve energy. They also allow their body temperature to vary wildly compared with other mammals. Whereas humans hover within a degree of 38°C, the three-toed sloths Pauli studied allowed swings of nearly 5°C as the forest cooled or warmed around them. That saves a lot of energy, because maintaining a core body temperature is energetically expensive.

But sloths still need a way to warm up. Shivering, favoured by most warm-blooded animals, is for creatures with energy to burn. Instead, three-toed sloths climb higher into the canopy each morning to make the most of the sun's generosity. Sloths also can't jump.

But even beyond saving energy, the sloth's characteristic slow-motion upside-down walking might have another benefit: camouflage. One of the sloth's main predators, the harpy eagle, relies on seeing its prey move. Hanging upside down, completely still, for hours on end seems to do the trick. Sloths can do this in part thanks to their long, curved claws, which their giant ancestors used to excavate tunnels, but now operate more like coat hangers. The constant grip is made possible by a lattice of tendons in the hands and feet that draw the digits closed while at rest.

But there seems to be more to their muscular abilities than that. We usually think about muscles as doing one thing well, says Michael Butcher, a zoologist at Youngstown State University in Ohio. An Olympic weightlifter, for instance, has muscles capable of small, powerful movements, whereas a marathon runner's muscles are geared towards sustaining long periods of exertion. "But sloths break that rule," he says. They have an uncanny ability to resist fatigue, as well as a surprising amount of strength.

To better understand how they do it, Butcher dissected a dozen sloth cadavers. He was surprised to see they had very little muscle tissue – roughly 10 per cent less than you find in other arboreal mammals. But what muscle there is appears to be extraordinary. Most strikingly, sloth muscles seem to contain a unique set of enzymes that confers tolerance to heavy accumulations of lactic acid, which may help them resist fatigue as they hang out or move in super-slow motion.

For all these fresh insights, there is still a lot to learn about sloths. We don't know why they climb all the way down to the forest floor to defecate, for instance, never mind why they bury the mess. It doesn't seem very frugal.

One thing is clear, though: the more we learn about these extraordinary creatures and their unhurried lifestyle, the easier it is to appreciate how diet and metabolism can drive evolutionary adaptation. ▮

FIGHTING FUNGI

Fungi are a diverse and distinct kingdom of organisms, neither plant, animal nor bacterium. Their activities are crucial for the survival of many ecosystems – although we may blanch at some of the means they use to ensure their success.

FUNGI ensure that land-based ecosystems thrive. Their activity is largely responsible for the breaking down and recycling of bulky, dead plant tissues. By releasing the nutrients locked inside material rich in lignin and cellulose, from leaves and twigs to mighty trunks, they ensure that further generations of plants can grow and the animals that depend on them can thrive.

They probably also created such ecosystems in the first place, helping to make the first soils and assisting photosynthetic organisms in colonising the land. One particular group, mycorrhizal fungi, feed nutrients and water directly into plant roots, and are paid for this service with sugars from the plant. In this intimate relationship, which probably evolved just as life was getting a toehold on land about 450 million years ago, fungi colonise the fine roots of plants and extend into soil as long, thin tubes called hyphae, the better to gobble up nutrients for both.

So far, so benign. But to crunch your way across a meadow or through a wood on a crisp winter's day is to traverse a battlefield. That rural tranquility is a mere veneer. Beneath the soil, in those piles of falling leaves or that moss-covered tree stump, a war is being waged.

You might see the standards of some of the troops standing proudly above the surface: perhaps a field mushroom or a bracket fungus. The passivity is deceptive. Out of sight, scenes of peculiar barbarism and brutality are being played out. One-on-one combat, stealth assassination, chemical warfare, even mind control: when mushrooms get martial, the Geneva Conventions most definitely do not apply.

A collection of fungal hyphae is called a mycelium. Woe betide a mycelium encountering a different species of fungus – and as there are thousands of species in a typical woodland landscape, it happens often. This is when the battle lines are truly drawn.

For some fungi, war means bare-hand killing. Soil-dwelling fungi of the genus *Trichoderma*, for instance, coil around a victim's hyphae and use mechanical force and enzymes to penetrate it, sucking out food.

Mostly, though, the means are more insidious. We are familiar with some of the volatile chemicals that fungi produce, such as the odour of cooking mushrooms or the smell of rot. When fungal species encounter each other, chemical warfare often ensues. Some, such as a versatile assassin called the sulphur tuft, produce agents such as sesquiterpenes that are as damaging to fungi as nerve gas is to humans, and quinolinium compounds like those used in commercial

›

ENGABITO/ISTOCK PHOTO

The cap of a fungus shows little of the drama going on beneath

fungicides. The ubiquitous turkey tail fungus, on the other hand, is a poisoner. It secretes enzymes into the food sources on which the opponent fungus feeds, killing and dissolving the other combatant from the inside so its territory and food can be taken as the spoils of war – assuming it avoids its own predators.

Fungi aren't just aggressive to their own kind. Nematodes – minute, worm-like, soil-dwelling creatures – are favoured prey, forming a nutrient-rich supplement to their diet. Fungi have evolved nematode traps of varying complexity, including adhesive protrusions that emerge on the hyphal surfaces like lethal lollipops, and adhesive nets and nooses to strangle the unwary.

Equally macabre demises are brought about by fungi that produce spores that stick to the outsides of nematodes, or use hooks and protrusions that lodge within the worms' mouths. Irrespective of how the nematode has been incapacitated, the next step is the same: the fungus pushes its hyphae into the worm's body and liquidises its body contents.

Insects and other arthropods aren't safe, either. Their multilayered exoskeletons, made of waxes, lipoproteins and often anti-fungal compounds, protect their vulnerable interiors rather as an army tank protects its human cargo. But some fungi penetrate these defences and even evade haemocytes, specialised warrior cells sent out by the insect's immune system to seek and destroy invaders. Once inside, one group of fungi, Entomophthorales – its name means "insect destroyer" – choke its victims to death by blocking their spiracles, or breathing tubes. Killers from Helotiales, meanwhile, spread through the body cavity in a yeast-like form, exuding deadly toxins.

There is more to studying the military tactics of mushrooms than pure voyeurism. Even in the late 19th century, the powdery spores of white muscardine (*Beauveria bassiana*) and green muscardine (*Metarhizium anisopliae*) fungi were mass-produced in Russia and the US in an attempt to control the insect species they parasitise, among them the Colorado potato beetle.

The high cost when compared with chemical insecticides, and complications in production, storage, distribution and application, meant these initiatives met with limited success. But concerns about the environmental consequences of chemical control mean "biocontrol" is coming back into favour. With it, there is an increased interest in how fungi's natural chemical arsenals work. Fungal insecticides have the decisive advantage that they can be selected to target specific organisms, minimising unintended harm to other species.

Fungal aggression towards microbes is the origin of our best-known antibiotic, penicillin. Molecular biology tells us that within every fungal genome, there are multiple pathways for producing similar killer chemicals – yet just a few are produced when these fungi grow alone in the lab. It is only in the heat of a fight that they turn on the production of a diverse antimicrobial arsenal. Understand what triggers this arms race, and better drugs could be within our grasp. ■

PDF NEWSPAPERS and MAGAZINES: WWW.XSAVA.XYZ

BEETLE MANIA

The arthropods are the most successful animal group in the world. They have hard exoskeletons, segmented bodies and jointed legs, and they include insects, spiders, scorpions, crabs and centipedes. But among even the arthropods, one group stands out for the sheer scale of its success – the beetles.

VITALSSSS/ISTOCK PHOTO

WHEN biologist J. B. S. Haldane was asked by a theologian back in the 1940s what we could infer about the mind of the creator from the works of creation, he supposedly replied, "an inordinate fondness for beetles". The story is almost certainly apocryphal, but it reveals both an undeniable truth and an open question. Judging by their sheer numbers, God is certainly fond of beetles. But just how fond?

The number of beetle species is just one lacuna in our knowledge of these extraordinarily successful creatures. Another is what makes them quite so successful. As we slowly fill in the gaps, we are beginning to appreciate the unique insights these insects can give us. Whether we want to understand evolution, the workings of the biosphere or how plate tectonics has shaped the continents, beetles hold the answers.

New beetle species have been described at an average rate of about four a day since 1758, when Carl Linnaeus started cataloguing plants and animals using the two-part Latin scientific names we know today. Towards the end of the 20th century, there was general agreement that the total count was heading towards 400,000 species, based on specimens housed in the world's museums and carefully documented in 250 years of scientific journals and monographs. Compare that with 5500 mammals, 10,000 birds, 85,000 molluscs and 250,000 plant species, and it is clear that beetles far outstrip any other multicellular organisms in diversity, perhaps quietly brushing aside nematode worms.

In 1982, however, this emerging consensus was shaken to the core. Entomologist Terry Erwin was conducting a census in a Panamanian rainforest, hauling fogging machines up into the canopy and retrieving the insects that fell from the branches in bins and sheets below. From just one evergreen tree

›

> **"The emergence of flowering plants increased beetle species 600-fold"**

species, *Luehea seemannii*, he collected 1200 species of beetle, some unknown to science. Using simple mathematics and modest assumptions about how some beetles were specific to certain trees, he extrapolated the number of beetle species present in all 50,000 known tropical tree species. It came out at around 12 million.

Using slightly different ecological assumptions, others came up with anything from 3 million to 33 million beetle species. This was bonkers. Not only was the deity's love of beetles far more ardent than anyone thought, but our estimates of that ardour were now at odds by more than an order of magnitude. Although arguments still rage, most models seem to agree that there are at least a few million beetle species.

So why are beetles so successful? We have long had ideas, but only recently did they gain some experimental backing.

Beetles began to proliferate in the Carboniferous Period between 350 million and 300 million years ago. At some point, the front pair of wings of their precursor beetloid acquired a leathery texture, while the hind pair remained delicate and membranous. The tough front wings gave protection to the folded back wings when the creature shimmied into a tight crevice under a bit of loose cycad bark or a fallen tree fern. With the insect still able to fly at will, these structures became indispensable armour – the elytra, or wing cases, of modern beetles.

In what has become an instant classic of the entomological literature, in 2016, David Linz at Indiana University Bloomington and his colleagues tested the importance of the elytra by exposing beetles to various environmental stresses. Surgically trimming the wing cases from the red flour beetle, *Tribolium castaneum*, they measured damage over time to the membranous hind flight wings, survival against attack by *Pardosa* wolf spiders, whether the beetles dried out in low humidity and how the beetles coped in -4°C cold for 24 hours. In all cases, morbidity and mortality were greater in the trimmed beetles than in intact specimens. The elytra really were life-saving armour.

Beetles enjoyed one other lucky break: the advent of flowering plants between 120 million and 100 million years ago. Their emergence seems to have led to beetle species increasing 600-fold. Today, the main plant-feeding beetle groups are the Phytophaga – leaf beetles, longhorns and weevils. Their 135,000 species, making up 80 per cent of all catalogued herbivorous beetles and half of all herbivorous insects, mostly feed on flowering plants. They will feast on just about any plant part, too, from tubers, roots, shoots and bark to leaves, buds, flowers, seeds and fruits. But in certain temperate parts of South America, South Africa, Australia and New Zealand, a few ancestral species – just 225 in total – feed on "primitive" non-flowering plants such as conifers and cycads, which dominated Earth's earlier flora. The nutrient-rich, pollen-bearing male cones (strobili) of conifers are the staple of most of these insects.

Beetles' hardiness and dietary flexibility means they have come to thrive in a quite extraordinary range of environments. A world away from the exuberant beetle throngs in the cloud forests of Central America, for example, beetles form the main plank of biodiversity in one of the driest places on Earth, the Namib desert. Wherever they occur, their ubiquity and persistence make them unique witnesses to ecological continuity and the mechanisms of environmental change. ▮

MARIMA-DESIGN/ISTOCK PHOTO

BRAINY BEES

We have known for decades that bees working collectively are capable of great things – not least symbolic language in the form of their waggle dance, which they use to share information about the location of food sources. But in the past few years, apian skills have been shown to have truly mind-boggling complexity.

THE capabilities of bees are often put down to swarm intelligence, but over the past few years, findings have been trickling in suggesting that individuals deserve more credit. Bees can follow intricate rules, distinguish between patterns in nature, sort sensory stimuli by shape and colour and even have a rudimental ability for mathematics.

To test the limits of bee abilities, Olli Loukola at Queen Mary University of London and his colleagues taught bumblebees to roll small plastic balls into holes to win slurps of sugary water. Soon, the bees were devotedly operating the miniature vending machines, frequently finding shortcuts to the sweet prize – some even walked backwards, a behaviour that isn't natural to them. In another experiment, bees were trained to pull strings to release tasty rewards.

The string study, published in 2016, was arguably the first evidence of tool use in invertebrates, an ability previously reserved for birds and mammals, particularly primates. Other research has found that bees in the lab will only attempt a certain task if they have all the requisite information, implying a rudimentary form of metacognition.

They are also expert navigators, according to Joseph Woodgate, a behavioural ecologist who is also at Queen Mary University of London. By attaching miniature transmitters to bees and tracking them with radar, he has found that his subjects not only remembered where they had previously been, but also flew shorter, straighter paths as time went on. This demonstrates that they are constantly learning from the environment and innovating, rather than simply mechanically repeating themselves.

Findings like these have astounded biologists, who once assumed that bees resembled genetically programmed bots that were driven by instinct and incapable of solving problems or learning new skills.

Still, perhaps the biggest surprise regarding apian intelligence was the finding that the inner lives of bees are governed by complex feelings – mental states that are, in some ways, similar to human emotions like discouragement and contentment. In humans, feeling happy makes us respond more positively to ambiguous situations. To see if this happens in bumblebees, researchers gave sugar water to some bees but not others before they were set free to forage. Those that › received the syrup were more likely to seek out unknown sources of food.

Further tests confirmed the bees weren't simply feeling more adventurous thanks to a sugar high. Instead, the unexpected reward appeared to trigger a hit of the neurotransmitter dopamine, which – as it does in humans – left the bees in a more positive state of mind. Those that supped on sugar were also braver, venturing out sooner after scientists simulated a predator attack.

Lead author Clint Perry, also at Queen Mary University of London, didn't go so far as to assert that the adventurous bees were "happy" – a state that is hard enough to define in ourselves. But other research backs up the idea that bees have feelings too. Melissa Bateson at Newcastle University, UK, and her colleagues showed that vigorously shaking bees to mimic a predatory attack made them – in her words – "more pessimistic" and less likely to risk trying novel nectars, whose odours they didn't recognise.

The question of whether animals have human-like emotions is extremely controversial, making some scientists reluctant to state that bees have similar feelings to us. But even though bees can't fill out surveys to report on their levels of contentment, it would be surprising if they lacked at least equivalents of emotional states. An animal that couldn't feel something like fear when confronted with danger, or go-getter enthusiasm when food is plentiful, would have poor long-term prospects for survival.

And while it is unlikely that bees need to unburden themselves to their mates after a long day's slog in the meadows, there may be other ways in which, just like in human society, apian emotions prove themselves useful for the social cohesion of the group.

Together, these findings suggest that bees are at the forefront of insect cognition. Even more remarkably, the feats they have pulled off are normally associated with the largest and most recently evolved part of the human brain, the neocortex, which the minuscule bee brain lacks. This has left some neurologists scratching their heads about how insects solve problems we once thought required our own "higher" centres to crack. ■

THE SECRET LIVES OF TREES

Trees and other plants are far from silent observers of the world. They too communicate in complex ways, says Suzanne Simard.

PROFILE
SUZANNE SIMARD

Suzanne Simard is a professor in the faculty of forestry at the University of British Columbia, Canada

ANDREAS SPOHR/ISTOCK PHOTO

What have you discovered about the secret lives of trees?

The key finding is that trees are in a connected society, and that it's a physical network and that they trade and collaborate and interact in really sophisticated ways as a cohesive, holistic society.

From my training, and from the way we viewed forests or any plant community prior to that – at least in Western thinking – we didn't see plants as collaborative and linking. We thought that plants are solitary and compete to acquire as many resources as they can to increase their fitness. That idea isn't necessarily wrong. It's just that the way plants grow isn't simply by competition. They also collaborate, and there are synergies.

You have called it a "wood wide web" that consists of fungi as well as tree roots. What are fungi in these mycorrhizal networks like?

There are many different species of fungi, and they have niches and different physical and physiological structures. Some are really big pipelines. Some are little – tiny, fine threads. They all have different roles in extracting resources and moving things around. If you change the composition of that fungal community, you actually change how nutrients and carbon and water are moved around.

At first, some biologists were sceptical about the wood wide web. How did you convince them?

It was so tiring. I had to keep showing that these networks exist, and that plants are obligate mutualists with fungi; this means they need them to gather nutrients and water from the soil, especially in a stressful environment. That is what all seeds encounter when they are trying to germinate. The environment is a stressful place because seeds are small, there are predators, competitors – there's all sorts going on. And this little boost, the boost provided by the fungi, even though it's hard to measure, can make the difference between survival or death.

This doesn't challenge natural selection at all. Darwin wrote about the importance of collaboration in communities. It's just that it didn't gain traction like the idea of competition did. Natural selection results from more than competition. It involves a lot of different interactions and relationships between species and with the environment.

How did you find out that trees recognise their family members?

I was working on mycorrhizal networks, seeing if the networks were improving regeneration of seedlings around trees. And it seemed like the next logical question was: well, would the networks be able to

›

favour seedlings that were coming from the mother trees, the parent trees? I worked with Susan Dudley at McMaster University [in Canada] and we have found that kin recognition occurs in conifers. It's happening through mycorrhizal networks, and it's an important phenomenon in structuring these forest communities.

We were able to trace the carbon transferred between trees. We would label a mother or a sibling plant [by feeding it with carbon dioxide that contained a radioactive form of carbon] and then we would see that the carbon would transmit to a kin seedling, but not to a stranger planted nearby. I don't know how they recognise their kin, but I assume it's by chemicals because when we allow seedlings to connect with the mother trees or with their siblings, through these mycorrhizal networks, we get responses much more dramatically than if they connect with non-kin. It changes the rooting behaviour. It changes their chemistry, the nutrition of the plants and the response to disease.

You have said that everything in all the wood wide web works rather akin to a brain.

The architecture of those networks follows a biological neural network. In your brain, neurotransmitters have got to move from different lobes in order for your thought patterns to emerge. So they have evolved to do that efficiently.

It turns out, the underground network in the forest is designed the same way. I think it's for efficient transfer of information and resources for the health of the full community. Not only that, but the chemicals that are moving in those networks include glutamate, which is one of the dominant neurotransmitters in brains.

Is it too much to suggest that, like in a brain, there is intelligence in this network, even wisdom?

From a purely biological, physical analysis, it looked like it had the hallmarks of intelligence. Not just the communication of information and changes in behaviour as a result, but just the pure, evolved, biological chemistry and the shape of the networks themselves spoke to the idea that they were wired and designed for wisdom. If you look at the sophisticated interactions between plants – and some of that happens through the networks – their ability to respond and change their behaviours according to this information all speaks of wisdom to me.

What about awareness? Are trees aware of us?

Plants are attuned to any kind of disturbance or injury, and we can measure their biochemical responses to that. We know that certain biochemical pathways are triggered to develop these cascades of chemicals that are responses to stresses and disturbances, like chewing by herbivores. And if they are so attuned to small injuries like that, why wouldn't they be attuned to us? We're the dominant disturbance agent in forests. We cut down trees. We girdle them. We tap them.

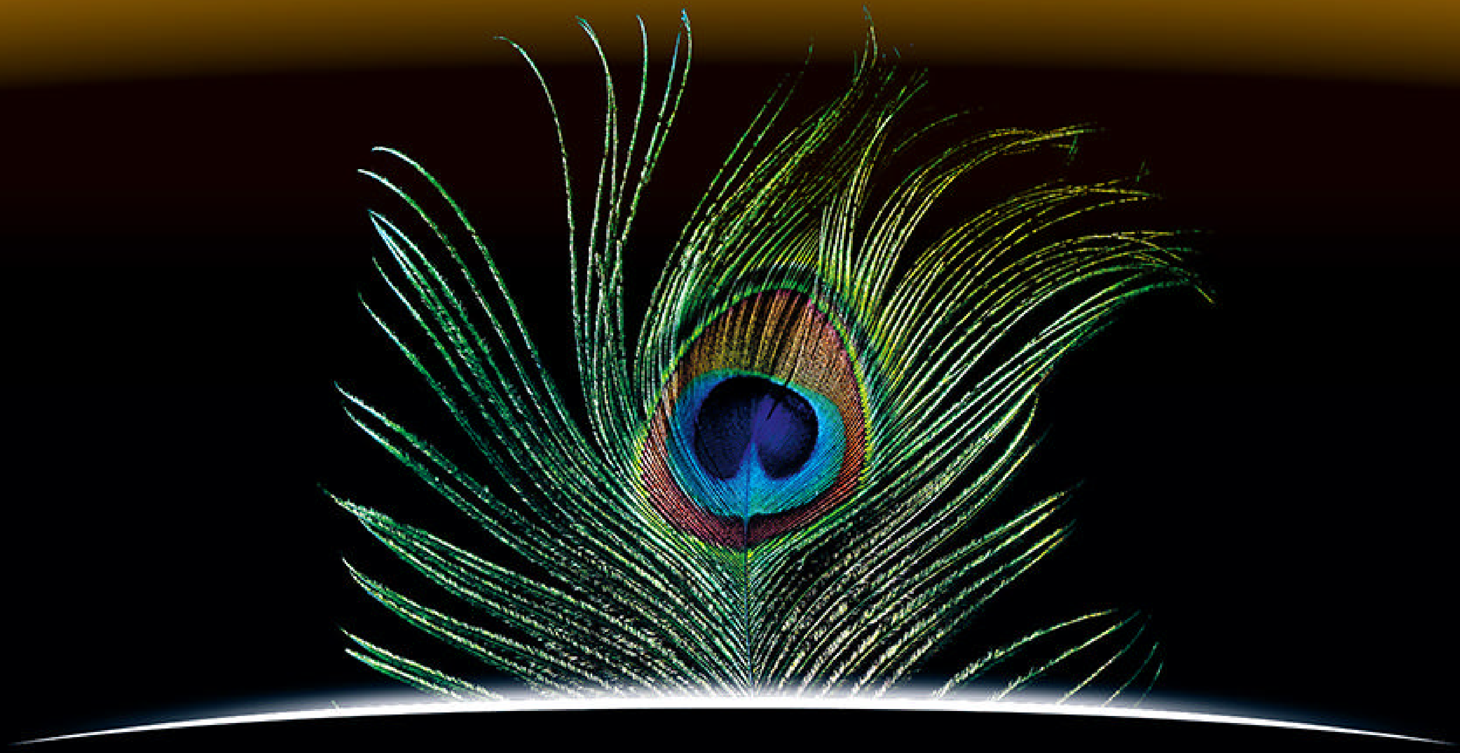
If I injure trees so much that they start to die, they start sending their carbon through their roots to their neighbours. They are responsive to us. We've proven it by doing our experiments. People go: "Oh, that's kind of scary". But why wouldn't plants be aware of people? They are aware of everything else. ■

New Scientist Academy

NEW ONLINE COURSE

EVOLUTION IS EVOLVING

It is biology's greatest theory, but our understanding of evolution is still a work in progress. Find out why.

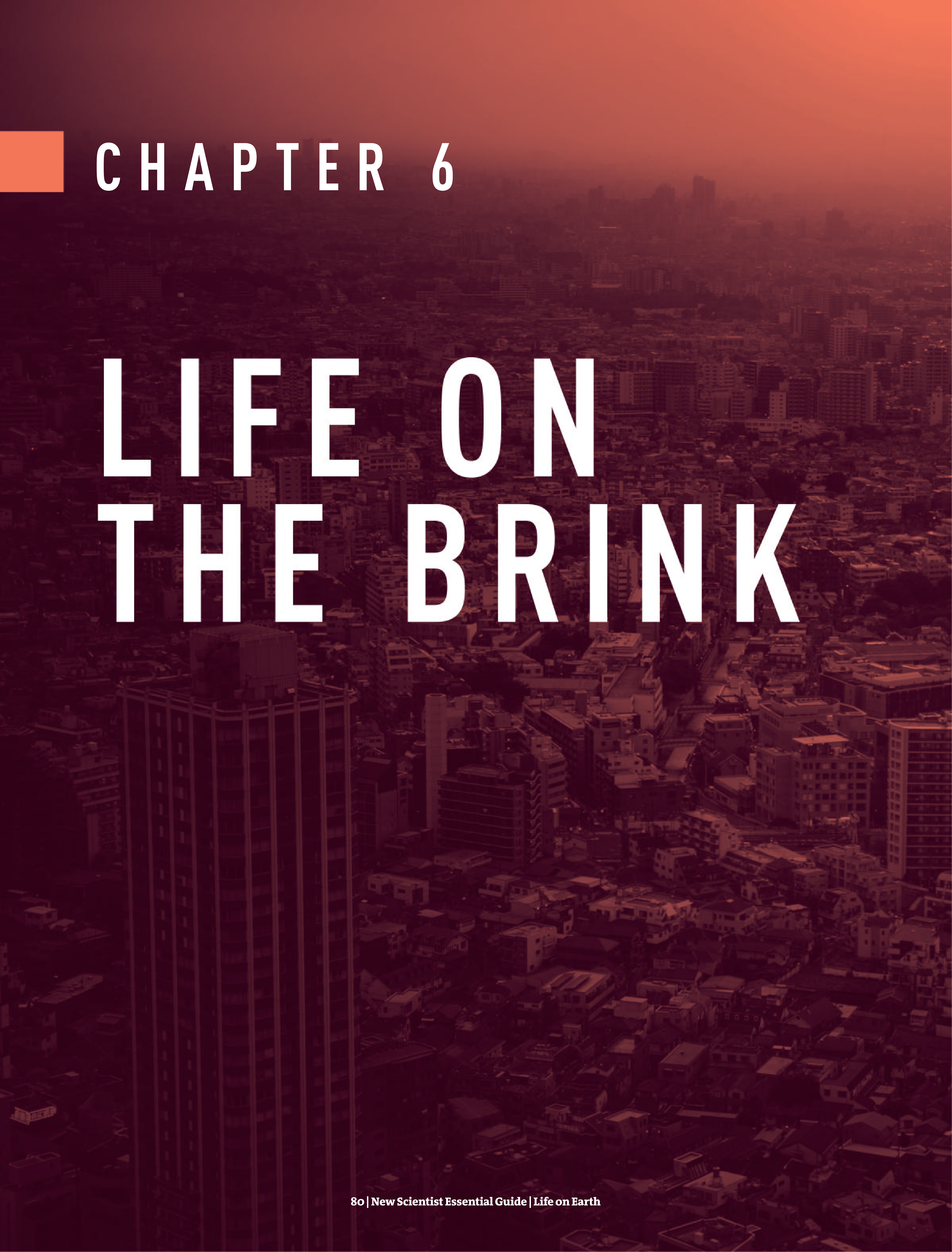


New Scientist Academy

Find the missing links in your understanding of evolution.

Evolution

The weirdest animals and plants ended up that way to survive. Uncover the strange secrets of evolution on our online course at **newscientist.com/mattersofevolution**



CHAPTER 6

LIFE ON THE BRINK

Life on Earth has come a long way. In its 3 or perhaps 4 billion years on this tiny blue dot, it has weathered many storms. Now the fear is that it is facing its greatest threat yet – us.

More than 70 per cent of ice-free land is now under human control and increasingly degraded. The mass of human-made infrastructure exceeds all biomass. Humans and domesticated animals make up more than 90 per cent of the mammalian mass on the planet.

Our actions now threaten about a million species – 1 in 8 – with extinction. All this has happened in a blink of an eye, geologically speaking.

BIODIVERSITY IN CRISIS

Earth's life isn't just beautiful. It ensures human survival, providing us with ecosystem services from fertile soils to pollination and clean air and water. Human population growth and overconsumption, plus the related problem of climate change, have set us at odds with the rest of the planet. But to protect nature's bounty, we first need to know exactly how we are harming it.

VIZERSKAYA/ISTOCK
PREVIOUS PAGE: NICOLAS McCOMBER

IN JUNE 2016, scientists at the University of Queensland in Australia confirmed what had been feared for some time: the Bramble Cay mosaic-tailed rat was no more. This small rodent eked out a lonely existence on Bramble Cay, a tiny dot of land at the northern end of the Great Barrier Reef. When Europeans first landed in 1845, the place was teeming with them. But frequent inundations caused by rising sea levels made life increasingly precarious. The creature is now literally a drowned rat.

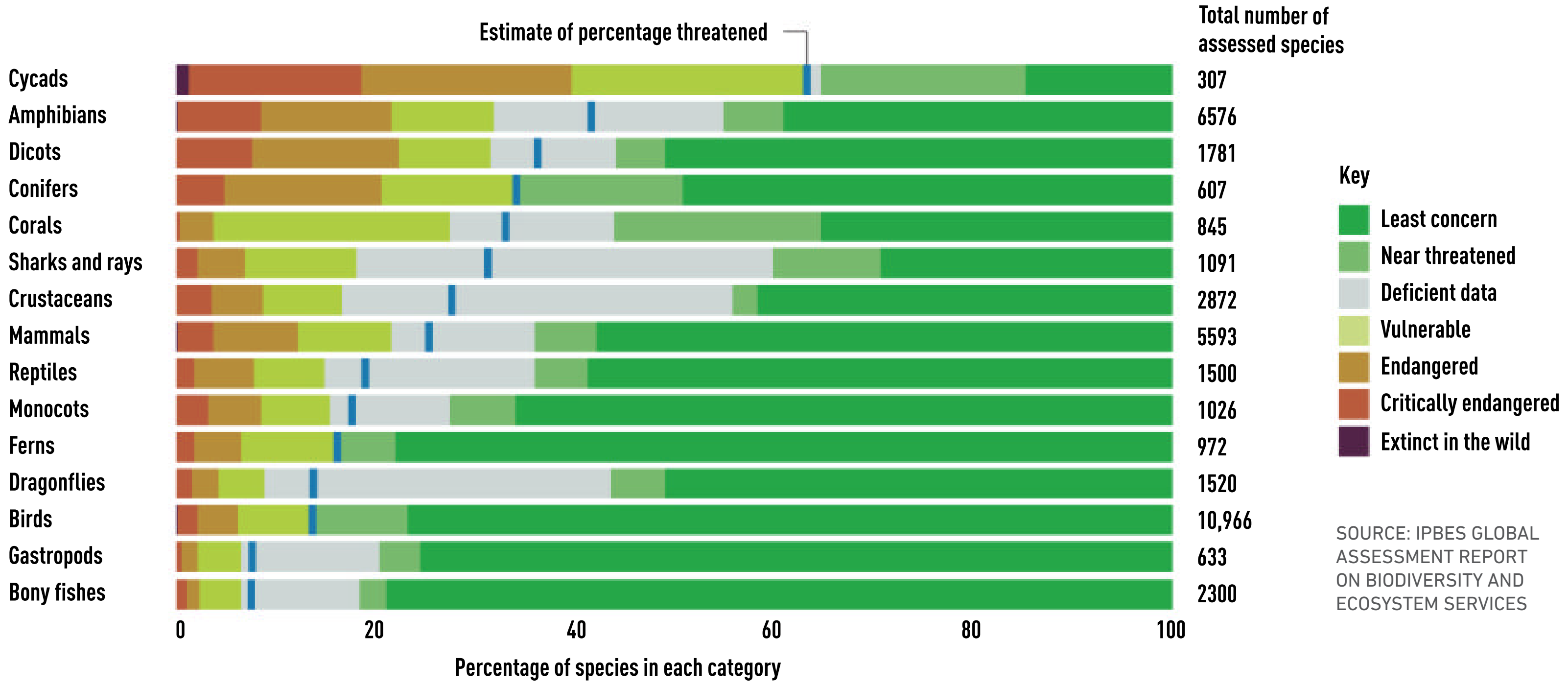
This is, in many ways, a familiar story. A once-thriving population, endemic to a small island, wiped out by human activity. But it is also a first. The Bramble Cay mosaic-tailed rat is the only species that we know for certain was driven extinct by climate change.

We are thus in an era where two great environmental anxieties – climate change and biodiversity loss – are converging. Biologists expect many more species to go the way of the rat. If we aren't already in the midst of the sixth mass extinction, we soon will be.

←
Turn back to page 60 for more on the previous five mass extinctions

You would have to be living under a rock not to have heard about the biodiversity crisis. While climate change is a new and present danger for many species, since about 1500, expanding human activity has condemned vast numbers of mammals, birds, amphibians and reptiles to an early grave. Now worries have spread to smaller creatures that

Current global extinction risk in different species groups



SOURCE: IPBES GLOBAL ASSESSMENT REPORT ON BIODIVERSITY AND ECOSYSTEM SERVICES

actually do live under rocks, in leaf litter, in dung heaps and in puddles and ponds. Even insects are reportedly in massive decline.

But just working out what is going on with biodiversity soon meets a fundamental problem: there is an awful lot of it, and counting it is hard work. You need legions of biologists in the field sampling, sampling and sampling, going back to the same places again and again to capture long-term trends. This isn't glamorous or sexy science, and the legions aren't there.

It doesn't help that biodiversity is something of a nebulous concept. The term first appeared in the 1980s, and came into popular usage after the Convention on Biological Diversity was unveiled at the Rio Earth Summit in 1992. But its meaning is surprisingly hard to pin down.

The simplest measure of global biodiversity is "species richness", which just means the number of species alive right now. This isn't known; current estimates range from 2 to 10 million, not including bacteria and archaea. So richness is usually measured in terms of its evil twin, the extinction rate.

Dire warnings on that score are nothing new. In 1979, UK environmentalist Norman Myers predicted in his influential book, *The Sinking Ark*, that a million species would be driven to extinction by the year 2000.

To the best of our knowledge, that hasn't happened. Many extinctions have been documented, but nowhere near a million. The International Union for Conservation of Nature (IUCN)'s Red List of Threatened Species, one of the most authoritative databases, documents just 866 recent extinctions. That is less than 1 per cent of all 91,000 species on the list and a negligible fraction of the estimated number on Earth. A further 757 are listed as "possibly extinct". But 44,148 are of "least concern", red-list jargon for not under threat of extinction.

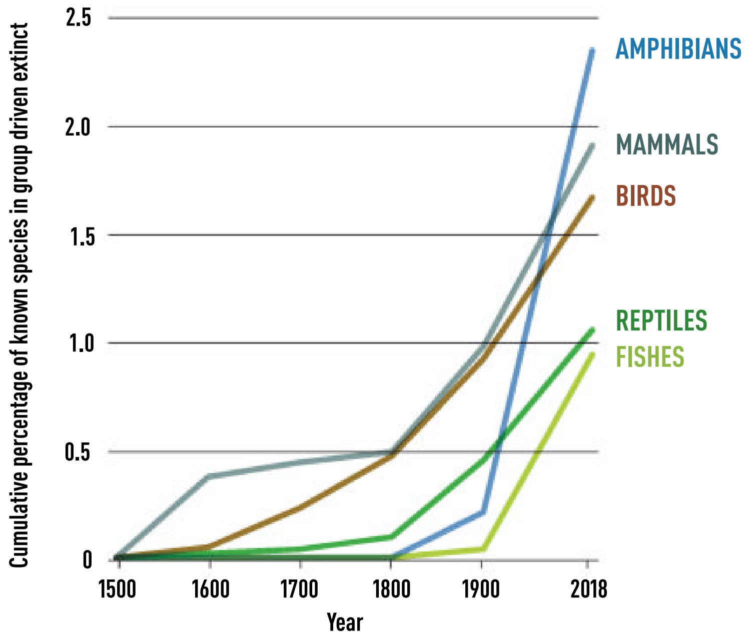
Species have been going extinct for billions of years without human intervention. To assess our contribution, we need to know the background or natural rate of extinction. From the fossil record, this is typically calculated to be about one extinction per million species per year. On that measure, to have snuffed out nearly one in 100 of the species on the IUCN list looks very bad. Extinction rates are about 1000 times above the background rate.

Then again, most of what we know about the decline of biodiversity from the IUCN list concerns a limited group of large and fairly obvious animals, such as mammals, birds and amphibians. All of these are in trouble. A quarter of the 5488 mammal species on the list are threatened. For amphibians, it is 41 per cent; for birds, 13 per cent.

But extinction rates are a blunt measure of the biodiversity crisis, because species often become less numerous but rarely go entirely extinct. A more detailed picture is provided by the Red List Index, which tracks how rapidly mammals, birds, amphibians and corals are progressing through the categories, from vulnerable through endangered, critically endangered, extinct in the wild and extinct. By this measure, biodiversity is clearly in decline.

But this fails to capture another critical consideration, known as functional diversity. Species

Extinctions since 1500



SOURCE: IPBES GLOBAL ASSESSMENT REPORT ON BIODIVERSITY AND ECOSYSTEM SERVICES

fulfil useful roles in ecosystems, like pollination. It is about whether enough of the right species are there to provide those crucial ecosystem services.

The best measure of this is arguably the Living Planet Index, devised and maintained by conservation group WWF and the Zoological Society of London. This crunches data on 19,500 populations of more than 4000 vertebrate species from around the world. It, too, contains a stark warning. The 2016 version of the index showed that since 1970, the abundance of vertebrates has declined by 58 per cent. Over the past 50 years, we have lost more than half of the big animals on Earth.

That seems bad. But big, rare animals are possibly quite unrepresentative of life as a whole. To really understand what is happening to biodiversity, you need to know about the small and unglamorous things that do most of the work keeping ecosystems ticking over: insects, and also fungi, algae, crustaceans, molluscs and so on.

In 2018, UK TV presenter and naturalist Chris Packham captured the antsy zeitgeist surrounding these creatures when he tweeted: "I've been in my garden in Hampshire for the last couple of days. Sunny, plenty of wildflowers. Not a single butterfly. Not one. Nothing. And in the woods a handful of Speckled Woods. I think we are at a point of absolute crisis in our countryside."

Every conservationist has an anecdote of this kind. One example is insect splats. A few decades ago, you would return home from a drive in the country to find your car smeared with pureed flies. Nowadays, insect strikes are a rarity. In 2004, an informal study carried out by the UK Royal Society for the Protection of Birds using cardboard "splatometers" attached to the front of cars recorded an average of just one splat every 8 kilometres.

But these are anecdotes, not data. Perhaps that is why a research paper published in 2017 caused such a stir. It was the result of surveys carried out in 63 nature reserves in western Germany, starting in 1989. Every year, in early spring, the team pitched tent-like insect traps in one of a number of carefully selected locations to catch low-flying insects. They were left up throughout the spring, summer and early autumn, then emptied every few days and their haul of insects weighed.

This is exactly the sort of meticulous, long-running biodiversity experiment that we desperately need if we are to understand what is going on. And the findings were horrific. In the early 1990s, a single trap would typically catch around 8 grams of insects a day. By the mid-2010s, that had slumped to just 2 grams. The number of flying insects in spring and summer had dropped by an average of 75 per cent.

The finding was quickly dubbed "insect Armageddon". To many, it fit with what we already knew. UK butterfly abundance has declined three-quarters in the past 30 years. Europe's grassland butterflies declined by 50 per cent between 1990 and 2011; wild bees and moths have fallen by similar amounts. The German study was simply the first to confirm an overall, dramatic decline in all flying insects.

Nonetheless, there are reasons to think things aren't that cut and dried. Most of the collection sites in the German study were only sampled once in 27 years. It is possible, though unlikely, that the results indicate variation in space rather than time. And it only measured the total mass of insects caught in the traps, which arguably doesn't capture diversity.

The story of insect Armageddon also doesn't entirely chime with some other, even longer-running insect-trapping experiments. In 1964, researchers at the Rothamsted Experimental Station, now Rothamsted Research, in Hertfordshire, UK, began operating a nationwide network of 78 light and 16 suction traps that has been collecting insects from the same locations ever since. The traps don't tell a story of universal massive decline. One 2009 study, for example, examined the catch from four suction traps over 30 years from 1973 and found no change in insect biomass at three of them.

In the UK, there have been declines in butterflies, moths, dragonflies and carabids. But other groups seem to be doing fine. Pest insects haven't gone down, and nor have aphids despite all the effort people put into controlling them. There is also a 42-year study › of insect populations in cereal fields in south-east England, which showed that some had gone down, some had gone up and some had stayed the same.

The basic problem is a lack of data – and that is for insects in the UK, one of the most intensively entomologised countries in the world. Elsewhere, the records are even worse.

In 2015, a group of conservation biologists based in France revealed the depth of our ignorance in a paper called "Mass extinction in poorly-known taxa". They pointed out that, even though all 15,528 known bird and mammal species are on the IUCN Red List, only 1 per cent of 1.4 million invertebrate species are. Of these, more than a quarter are classed as "data deficient". Those that have been evaluated tend to belong to larger and more charismatic groups: butterflies, dragonflies, corals and certain snails. "Invertebrates are still essentially unevaluated," they concluded.

These glaring gaps in our knowledge mean that any claim of a global biodiversity crisis among insects and other invertebrates, however plausible, must remain an untested hypothesis.

That isn't to say that we can't make educated guesses. One group of invertebrates for which we have quite good data is molluscs. According to the IUCN, this group has been hit the hardest of any on the red list, with 297 of 744 species listed as extinct. Freshwater mussels are suffering, and there are a large number of extinctions among gastropods (snails and slugs), especially land snails that evolved in isolation on remote islands. These have been badly affected by invasive species and habitat destruction. One family endemic to Hawaii, for example, comprised 325 species in around 1900; only 18 are left.

Molluscs might just be particularly vulnerable to extinction. But if their fate is representative of other invertebrate groups, the French team estimated that up to 13 per cent of all species have gone extinct since 1500. That would make Myers's prediction of a million extinctions look about right. But the Rothamsted insect survey highlights something rather counter-intuitive: biodiversity can go up as well as down.

The main targets of light traps are moths, and the Rothamsted scheme has been catching them in large numbers for decades. Since the insect survey began, more than 60 species have disappeared from mainland Britain, and the abundance of large moths has fallen by

58.1%

OF THE WORLD'S LAND SURFACE HAS SEVERELY COMPROMISED BIODIVERSITY

SOURCE: BIODIVERSITY INTACTNESS INDEX

50%

AVERAGE REDUCTION IN ANIMAL POPULATION SIZE BETWEEN 1970 AND 2012

SOURCE: WWF/ZSL LIVING PLANET INDEX

5488

MAMMAL SPECIES THREATENED WITH EXTINCTION, 25 PER CENT OF TOTAL SURVEYED

SOURCE: IUCN RED LIST

about a third. Remarkably, however, this loss has been more than offset by new arrivals, probably as a result of climate change. In the same period, more than 100 new species have become resident in Britain, a third of them since 2000. In terms of species richness, at least, moth biodiversity has increased.

This pattern of local biodiversity increase due to incoming species is surprisingly common. Mark Vellend, a conservation biologist at the University of Sherbrooke in Canada, has documented it in plants, another critically important group for which we don't have enough useful data. In 2013, he and his colleagues published a meta-analysis of thousands of studies of local plant biodiversity from around the world. The surprise conclusion was that, overall, the level of change was zero.

In those terms, the story is one not of decline, but of homogenisation. At a global scale, there is a biodiversity crisis, but at smaller scales there are always new species coming in. It is a story that gets straight to the heart of the hottest controversy in biodiversity science today. If a species goes extinct but is replaced by a non-native one that performs the same ecological function, does that matter? What if it is replaced by two non-native ones?

If you care about biodiversity per se, then it matters. The loss of a species is irreversible, and marks yet another downward tick. As species disappear, ecosystems become increasingly homogenous, with more highly successful generalists like sparrows and fewer rare specialists. But if we care about biodiversity because of the ecosystem services life provides, then one species of tree or dung beetle is very much like another.

From this second perspective, how much global biodiversity loss is too much? Unsurprisingly, we really don't know. In 2009, Johan Rockström at Stockholm University, Sweden, and his colleagues started an attempt to quantify it with their concept of "planetary boundaries". They proposed there were nine support systems essential for life to flourish, including the climate, fresh water, nutrient cycles, the ozone layer, ocean pH and biodiversity.

Throughout the past 10,000 years, these systems have been remarkably stable and resilient to change, creating a benign space for civilisation to flourish. But human activity is now threatening to perturb some or all of them past a point of no return. The aim was to identify those points of no return and so define a "safe operating space for humanity".

In the original paper, biodiversity was measured using the most basic metric, the global extinction rate. The provisional boundary the researchers set was 10 extinctions per million species per year, around 10 times the background level. Their guess of the actual extinction rate was 100 extinctions per million species per year.

If so, that would make biodiversity the most dangerously overshot of all nine boundaries, even worse than climate change and the disturbance of the nitrogen cycle through overuse of fertilisers. But this was only a guess. Rockström's team freely admitted that the biodiversity boundary was a "very preliminary estimate" and that more research was needed to define it with greater certainty.

A few years later, they came back with an answer. Out went biodiversity loss; in came something called "biosphere integrity". This was a composite of two metrics: functional diversity and genetic diversity, which supposedly reflects the biosphere's long-term capacity to withstand and adapt to change through evolution. But this, too, proved impossible to measure.

The consensus now seems to be that the boundaries approach was useful for focusing minds on what might constitute a dangerous level of global biodiversity loss, but that, fundamentally, it was barking up the wrong tree because biodiversity loss is a gradual change rather than a critical transition after which the biosphere collapses. The mistake, according to the late Georgina Mace at University College London, was thinking that biodiversity can be measured one simple way. Instead, what we should concentrate on, she argued, is local boundaries. A "safe" operating space for any local area might have so many wild species, so much forest cover and so on, to buffer us from threats such as climate change.

Despite all the uncertainties and disagreements, nobody is in any doubt that biodiversity is in decline and that humans are to blame. But the decline need not be terminal. Until a species actually goes over the brink, there is still hope we can bring it back. For instance, many great whale species have seen their populations rise in recent decades thanks to conservation interventions. Hope – and life – springs eternal. ■

JREDEN/ISTOCK PHOTO

THE CALL OF REWILDING

It is possible to reverse species declines if we intervene wisely. One much-discussed idea is rewilding: returning vast tracts of land to wilderness. But rewilding isn't an easy win – and debates rage about how to manage it.

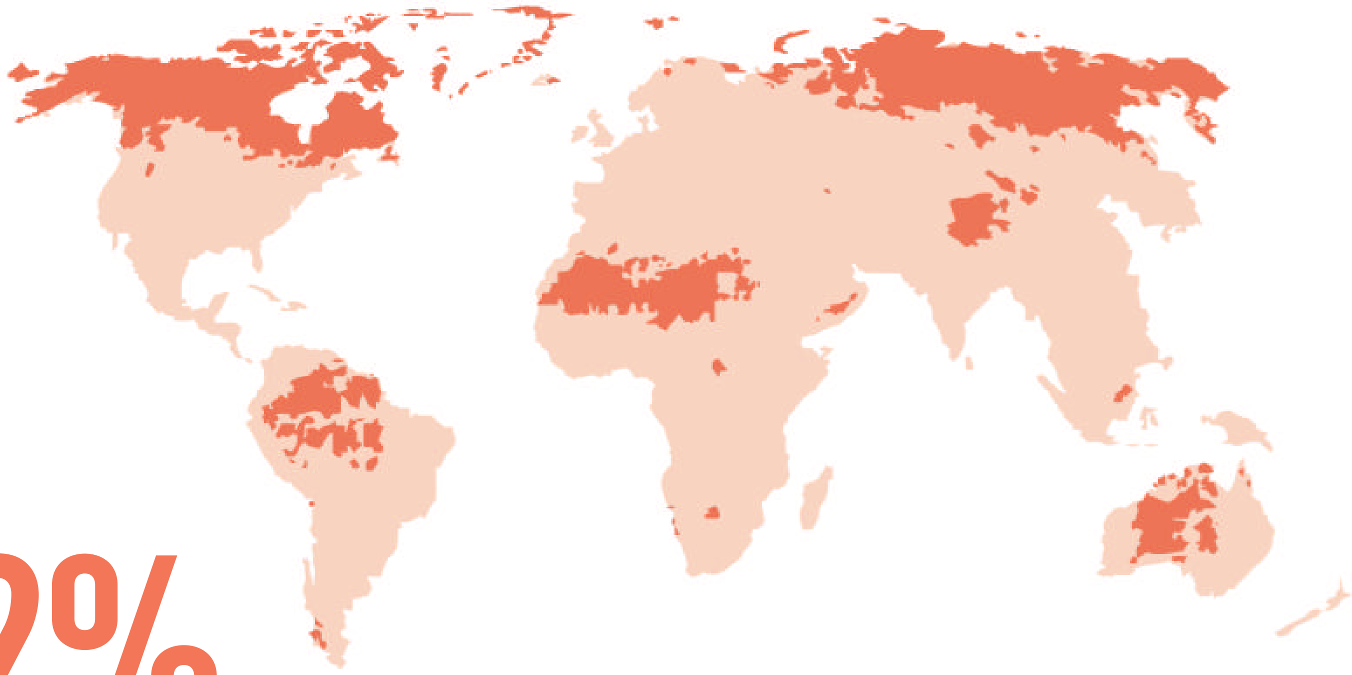
Bison thrive in a rewilded Yellowstone National Park in the US

THE original concept of rewilding is attributed to ecologist Michael Soulé at the University of California, Santa Cruz. In 1998, he published an essay outlining a new approach to conservation in North America. He advocated creating wildlife corridors between existing reserves, linking them up to create wildernesses large enough to support native carnivores such as wolves and bears, or even introduced ones such as lions.

The idea was underpinned by cutting-edge ecology, and specifically the concept of trophic cascades. This holds that ecosystems are principally shaped by the feeding behaviour of large herbivores and carnivores, the "apex consumers" largely absent from today's human-dominated ecosystems. Put them back in, so the logic went, and the ecosystem would automatically be restored to a healthier, more biodiverse state.

When Soulé proposed rewilding, the trophic cascade hypothesis was already being tested on the ground in Yellowstone National Park. The creation of the park in 1865 didn't stop rangers from shooting wolves, the natural apex predators. By the 1920s, they had been totally eradicated, with huge knock-on effects. The elk population exploded, causing bison to decline owing to competition for food, and beaver numbers to crash as elk overbrowsed trees next to rivers. Coyotes also boomed and gobbled up the pronghorn antelopes.

Remaining areas of wilderness in 2009



23.2%

OF TOTAL ICE-FREE LAND AREA

SOURCE: IPBES ASSESSMENT REPORT ON LAND DEGRADATION AND RESTORATION

In 1995, after a long campaign, wolves were reintroduced to Yellowstone. Almost immediately, the changes went into reverse. Trophic cascades were elevated to an iron rule of ecology. Ecologists John Terborgh and James Estes described them in a 2010 book on the subject as a "universal property of ecosystem functioning, a law of nature as essential and fundamental to ecology as natural selection is to evolution".

Of the many big and charismatic rewilding projects that have now been set up, most are essentially attempts to restore trophic cascades by reintroducing large animals, with the hope they will force the ecosystem back to an earlier state. One of the oldest and most famous is Pleistocene Park, a 160-square-kilometre nature reserve just north of the Arctic circle in Siberia. Since 1996, scientists there have been attempting to recreate the "mammoth steppe" that circled the northern hemisphere at these latitudes at the end of the Pleistocene Epoch 12,000 years ago.

Back then, most terrestrial ecosystems were dominated by huge herbivorous mammals, such as mammoths, rhinos, mastodons and ground sloths. They ate, trampled and dug up vast amounts of vegetation, kept grasslands free from trees and recycled nutrients through their copious dung. When they were wiped out by human hunters, the ecosystem was pushed into a radically different state: less open, less fertile and less biodiverse. With the megaherbivores gone, predators such as lions, bears and wolves called the shots, keeping populations of smaller herbivores in check through their own trophic cascade – until the predators were themselves hunted almost to extinction.

These waves of losses happened across the world. Some 100 genera of megafauna died out, precipitating a wave of secondary extinctions. The result was an overall simplification of food webs, a process called trophic downgrading. According to a review paper published in *Science* by Estes, Soulé, Terborgh and others in 2011, "the loss of apex consumers is arguably humankind's most pervasive influence on the natural world".

But how do you make a mammoth steppe when mammoths have long since bitten the dust? This touches on one of the most troublesome questions in rewilding biology. Rewilding implies a return to a previous state, yet restoring things to the way they were before humans often isn't an option. The original animals may be extinct, or the reintroduction of predators may provoke opposition from people worried about their own safety or that of their livestock.

In Pleistocene Park, the ecological role of mammoths is taken by herds of animals including musk oxen, elk, yaks, Yakut horses, European bison and reindeer, predated upon by existing populations of bears and wolves. According to park manager Nikita Zimov at ›

“Full ecosystem restoration requires vast areas for predators to roam”

the North-East Scientific Station in Yakutia, Russia, that is bringing results. The park is more biodiverse and more productive than the tundra it has replaced, he says, with knock-on benefits for ecosystem services, especially carbon sequestration.

In North America, however, Soulé’s original vision has been slow to materialise. An organisation called the Wildlands Network is gradually piecing together four separate wilderness areas across Canada, the US and Mexico, but progress is glacial.

In parts of Europe, though, Soulé’s ideas are alive and well, largely thanks to the fact that large predators are already making a comeback. This means trophic cascades can be restored simply by reintroducing herbivores, a “cannon fodder” approach that is the key to one of Europe’s grandest rewilding projects, in the Rhodope mountains straddling the Bulgaria-Greece border. The idea here is to create corridors between the area’s existing national parks to build a wilderness covering 2500 square kilometres, and to restore the deer population to provide food for the wolves and bears already living in the mountains.

Deli Saavedra at the non-governmental organisation Rewilding Europe, which oversees the project, calls this trophic change restoration. “It is not about looking back, but looking forward,” he says. “It is impossible to try to restore ecosystems to how they were, so we will end up with something new, but we still want them to be more natural – more wildlife, more natural processes – where nature can manage itself.”

The expectation is that deer and wolves will eventually recover to their natural population densities, and black vultures will follow thanks to the carcasses left after wolf kills. With plenty of deer to eat, the wolves should also be less likely to attack livestock, so human-wildlife conflict will be reduced.

Full trophic restoration of this kind requires vast areas for predators to roam – a wolf pack typically needs around 200 square kilometres. In landscapes fragmented by human activity, such as those of Europe and North America, this is rarely an option.

The answer can be to go halfway, restoring the herbivores, but leaving out the carnivores. This is the approach taken at another well-known rewilding project: Oostvaardersplassen in the Netherlands. This 56-square-kilometre site east of Amsterdam was reclaimed from the sea in 1967 and earmarked for industrial development. Nothing happened and it gradually ran wild, becoming an important bird habitat.

To keep this habitat from being swallowed by forest, in the early 1980s, its managers introduced cattle and horses to intensify the grazing. Red deer were added in 1992. Their activities have helped to create an ecosystem that ecologist Frans Vera, the site’s manager, has claimed is analogous to late Pleistocene Europe. But the lack of carnivores to devour the herbivores, and provide a natural brake on the amount they consume, means they must be culled or given supplementary food from time to time.

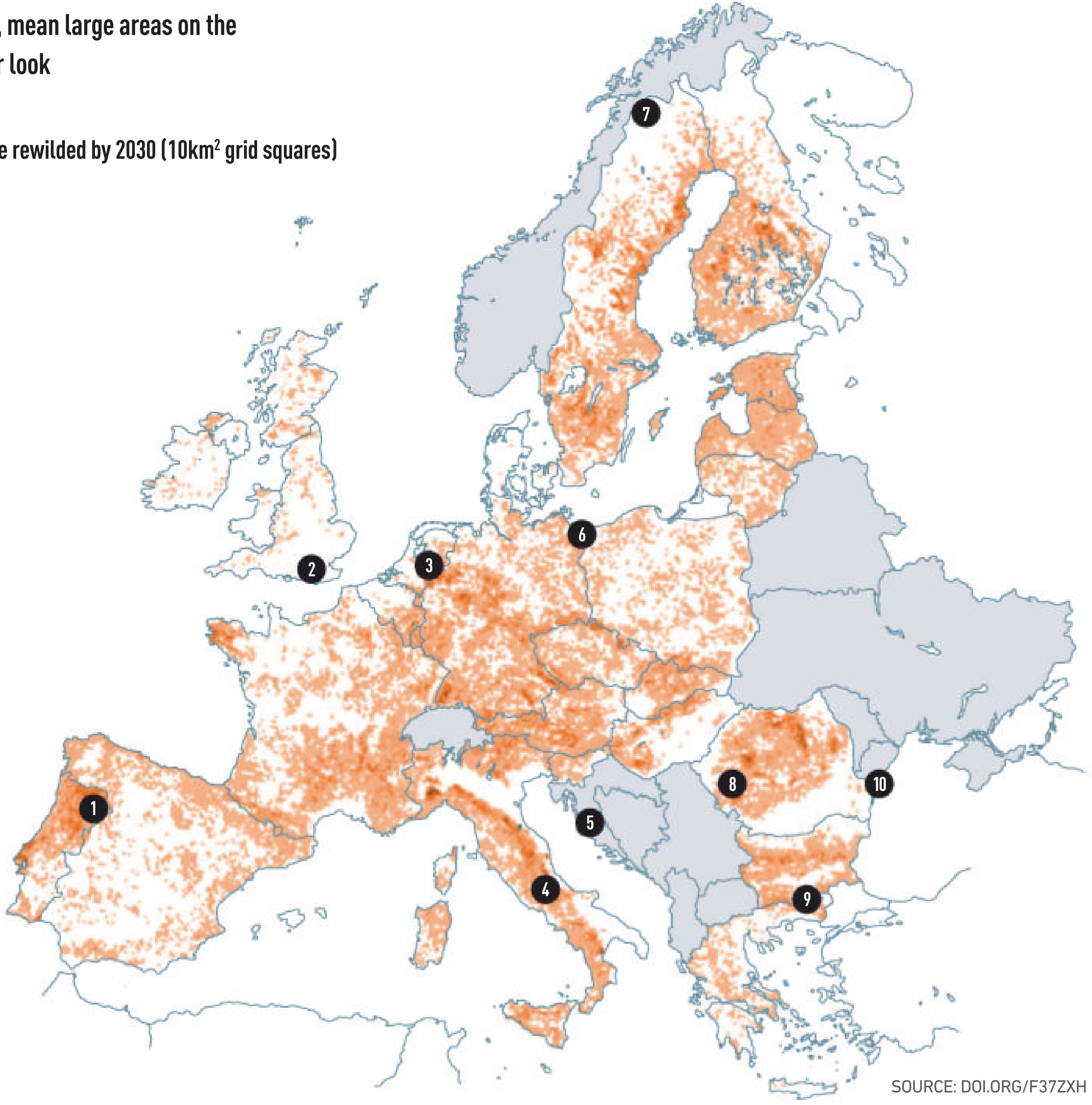
That raises questions as to whether such projects are true to the spirit of rewilding. But the concept of trophic cascades has itself recently come in for criticism. A 2018 study dug deep into the causes of

›

The abandonment of agricultural land, and some large-scale directed projects, mean large areas on the continent are gaining a wilder look

Percentage of land expected to be rewilded by 2030 (10km^2 grid squares)

□ No data
■ 1-5
■ 5-10
■ 10-15
■ 15-20
■ 20-30
■ 30-40
■ 40-50
■ 50-75
■ >75



SOURCE: DOI.ORG/F37ZXH

REWILDING PROJECTS

❶ WESTERN IBERIA
PORTUGAL

1000km^2

HABITATS: Old oak forests, steep river gorges, rocky heathland

SIGNATURE SPECIES: Iberian lynx, Iberian wolf, imperial eagle

❷ KNEPP
UK

(See main text)

❸ OOSTVAARDERSPLASSEN
NETHERLANDS

(See main text)

❹ CENTRAL APENNINES
ITALY

1000km^2

Ancient beech woods, open hillsides, alpine grasslands

Marsican brown bear, Apennine chamois

❺ VELEBIT MOUNTAINS
CROATIA

2200km^2

Mediterranean coastline, forests, deep canyons, alpine grasslands

Balke chamois, bear, wolf, lynx

❻ ODER DELTA
POLAND/GERMANY

2500km^2

Wetlands, forests, grasslands, bogs, dunes, beaches, open sea

White-tailed eagle, beaver

❼ LAPLAND
SWEDEN/NORWAY

35,000km^2

Boreal forests, mountains, glaciers, rivers, wetlands

Moose, wolverine, reindeer

❽ SOUTHERN CARPATHIANS
ROMANIA

1000km^2

Old-growth forests, rivers, mountains

European bison, wolf, lynx, bear

❾ RHODOPE MOUNTAINS
BULGARIA/GREECE

2500km^2

Oak and beech forests, grasslands, rivers, rocky slopes and cliffs

Black vulture, wolf, jackal

❿ DANUBE DELTA
ROMANIA/UKRAINE

1800km^2

Rivers, lakes, marshes, steppes, dunes, lagoons, salt marshes, forests

White-tailed eagle, pelican, jackal

SOURCE: REWILDINGEUROPE.COM

ecological change at the end of the Pleistocene at five sites in Britain and Ireland. This concluded that climate was much more influential than the presence or absence of megaherbivores.

Even in Yellowstone, the quintessential example, the strength of the trophic cascade effect has been questioned. The increase in beaver numbers following the reintroduction of wolves, for example, probably had less to do with the end of elk overgrazing and more to do with a separate programme to bring back beavers that took place soon after the wolves were returned.

A common criticism is that rewilding programmes have got ahead of the science and there is an urgent need for long-term experiments. But despite these concerns, rewilding is becoming a fixture of conservation biology. Most of it is happening entirely by accident, however, as huge swathes of farmland are taken out of productive use.

According to some estimates, within the European Union alone about 300,000 square kilometres of farmland will be abandoned between 2000 and 2030, an area about the size of Italy. Abandonment is also happening in the Americas, Australia and some developing countries, driven by low productivity, agricultural intensification and demographic change. Much abandoned land is in marginal areas such as uplands. Once deserted, most is simply left to its own devices.

This is known as passive rewilding. It may not get pulses racing in the same way as releasing charismatic mammals into a wilderness landscape, but in terms of land area, it is much more significant. That is a huge opportunity to revive biodiversity, but it needs to be supported by good science. What happens when we abandon land?

There are some indications. In 2014, a team led by Cibele Queiroz at the Stockholm Resilience Centre in Sweden reviewed 276 studies on the effect of farmland abandonment. Surprisingly, the researchers found that while some areas saw an increase in biodiversity, most didn't, especially in Europe. That is because traditionally farmed landscapes often create a wide range of habitats for wildlife. When human intervention stops, these biodiverse "cultural landscapes" disappear.

A classic example is Portugal's Côa valley, which has one of the highest levels of land abandonment in Europe. The area was once used for grazing cattle and running pigs, and also produced cork, honey, firewood and wild foods such as mushrooms. This low-intensity agriculture created a mosaic of habitats with high levels of biodiversity, supporting endangered Iberian lynx and Spanish imperial eagles. But as abandonment progresses, much of the Côa valley has become choked with dense scrub and forest, and is under constant threat of wildfires.

GALOPIN/ALAMY STOCK PHOTO

Wild garrano horses have been reintroduced to Portugal's Côa valley

It is a similar story in Japan. There, traditional terraced rice paddies are rapidly being deserted as the population dwindles and people switch from rice to wheat. Since 1961, half of the land once turned over to rice, amounting to around 2700 square kilometres, has been left to run wild. Another 1600 square kilometres is expected to follow in the next decade. Management of the paddies, through flooding and mowing, maintains a diversity of habitats and wildlife. When it ceases, the fields become choked with vines and invasive bamboos. Over the past 15 years, Japanese ecologists have documented a steady decline of insects, birds, amphibians and plants.

For some of these areas, a certain amount of active rewilding may be the answer. The Côa valley is one of Rewilding Europe's flagship projects. It plans to reopen the landscape by introducing horses and cattle. But given the scale of land abandonment, such active, well-planned intervention will remain a rare luxury.

One place where passive rewilding has been happening for decades is Moor House-Upper Teesdale National Nature Reserve in the UK, which was established in 1952. A vast area of bleak and soggy moorland, criss-crossed by streams and scarred by the remains of 19th-century lead mines, it represents exactly the sort of hardscrabble land where passive rewilding will mostly happen.

Starting in 1953, scientists began fencing off areas to see what happens when they are left ungrazed by sheep. In total, eight areas were enclosed and have now been undisturbed for 50 years or more. This experiment has been particularly relevant to the rewilding debate in northern Europe. For example, a common view of the British uplands holds that the Lake District National Park, a little to the west of Moor House, is a biodiversity desert destroyed by overgrazing, and that the answer is to take sheep off the land.

That's a thesis that has been tested at an enclosed plot called Bog Hill. Sheep have been excluded from this mossy mire for 65 years, but to the naked eye, the land inside and outside the enclosure is identical. Detailed studies of the soil and vegetation confirm that little has changed. The story is repeated at all the plots.

This suggests that bringing back nature by doing nothing can take an awfully long time, and taking the sheep away from areas such as the Lake District will do little or nothing for biodiversity. Without big herbivores, little happens.

In many places, then, passive rewilding looks to be an oxymoron. Just leaving land to go its own way may actually lead to a further reduction in biodiversity, not an increase. For that reason, active intervention may be required, at least in the beginning – including selective reintroductions.

If we do work it out, abandoned farmland represents our best chance yet of substantially rewilding large areas – and could ultimately lead to something not dissimilar to Soulé's vision of joining up existing reserves to create vast areas. ▮

We have seen the scale of the biodiversity crisis, and also the challenges and contradictions we have to face in solving it through the lens of rewilding projects. So what will it take to preserve the biosphere?

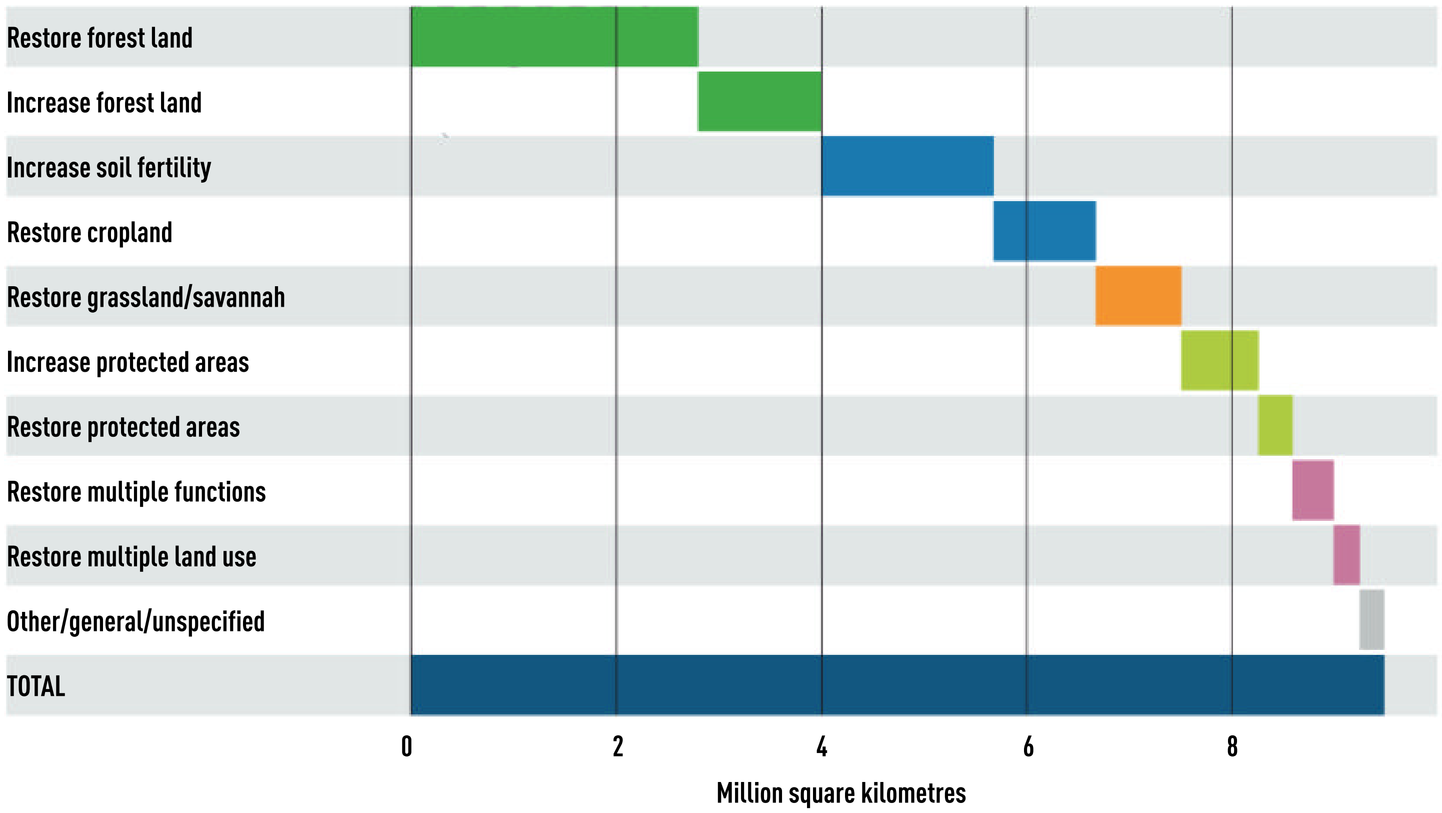
A RESCUE PLAN FOR NATURE

OUR relationship with nature started to sour around the start of the industrial revolution, but only really veered off the rails as the Great Acceleration kicked in after the second world war. In this period, booming population and trade and higher levels of prosperity led to an exponential growth of pretty much every measure of humanity's planetary impact: resource extraction, agricultural production, infrastructure development, pollution and habitat and biodiversity loss.

This plundering was a gamble that has long since ceased paying out. Degraded land already adversely affects the well-being of 3.2 billion people and costs more than 10 per cent of annual GDP in lost yields, poorer health and other negative impacts. Those are only going to increase. In a 2021 paper in the journal *Frontiers in Conservation Science*, an international group of scientists warned that the planet is facing a "ghastly future of mass extinction, declining health, and climate-disruption upheavals… this century".

It isn't that we have lacked good intentions in the ›

Total global commitments to ecosystem restoration



SOURCE: PBL NETHERLANDS ENVIRONMENTAL ASSESSMENT AGENCY, GOALS AND COMMITMENTS FOR THE RESTORATION DECADE

past. In 2010, the Convention on Biological Diversity (CBD) – one of three UN bodies to emerge from the 1992 Rio Earth Summit, along with the Framework Convention on Climate Change and the Convention to Combat Desertification – met in Aichi, Japan. It agreed 20 biodiversity targets to be met by 2020, from phasing out subsidies for activities that harm biodiversity to ensuring the genetic diversity of farmed and wild plant and animal species. Come 2020, and the final score was biodiversity nil, environmental destruction 20.

Take a key target on the amount of land to be given over to nature. It mandated protection for 17 per cent of land and fresh water and 10 per cent of the oceans by the end of 2020. Some progress was made, but neither goal was reached, with the current numbers being about 15 per cent and just over 7.5 per cent. Those areas that are protected are often poorly managed, too small and don't cover the full richness of Earth's environments: only some 42 per cent of 867 distinct types of ecosystem so far categorised are thought to be well protected.

There is evidence that we must expand protected areas to cover at least 30 per cent of the land and sea by 2030. A new group, the High Ambition Coalition for Nature and People, comprising more than 50 countries and co-chaired by France, Costa Rica and the UK, is now aiming to secure international agreement for this "30 by 30" pledge. In parallel, the UN has launched its Decade on Ecosystem Restoration. The aim is to prevent, halt and reverse the degradation of ecosystems – a daunting task, partly because so many are already degraded and must be restored.

Ecosystem restoration will be the key to success or failure over the coming decades. It takes many forms, depending on the ecosystem and how badly degraded it is.

At one end of the spectrum is passive rewilding, which simply means getting out of the way and letting nature do its thing. But there are limits to what this can achieve, as we have seen. At the other end of the restoration spectrum is active engineering of entire landscapes with mass tree planting, removal of alien species and damaging infrastructure, such as dams, and reintroductions of species.

This can be done. South Korea adopted an active reforestation policy in the 1950s following the Korean War. The total volume of wood in the country's forests increased from around 64 million cubic metres in 1967 to 925 million cubic metres in 2015, and forests now cover some two-thirds of the country. The Green Belt Movement founded in Kenya by Nobel peace laureate Wangari Maathai has planted tens of millions of trees across Africa, and inspired many similar projects.

›

BIM/ISTOCK PHOTO

HOW TO RESTORE AN ECOSYSTEM

How ecosystems are degraded by human activity varies – and ways to restore them differ too

FORESTS

Degraders: Clearance for infrastructure, agriculture and grazing; logging for firewood; pollution, invasive pests and wildfires

Restorers: Replanting native trees; conservation of plants and animals; rewilding

FRESH WATER

Degraders: Water extraction for irrigation, industry and homes; sand and gravel mining; dams, canalisation and drainage for agriculture; pollution from chemicals, plastics and sewage

Restorers: Controls on water extraction, fishing and mining; dam removal or redesign, restoring water flows to wetlands; wastewater treatment

OCEANS AND COASTS

Degraders: Overfishing and coastal clearance for aquaculture; plastic and nutrient pollution; wastewater discharge

Restorers: Sustainable fishing; wastewater treatment; pollution control; management and restoration of coral reefs; mangroves and seagrasses

GRASSLANDS AND SAVANNAH

Degraders: Conversion to cropland and pasture; overgrazing and soil erosion; unsustainable resource extraction; invasive species

Restorers: Active clearance of woody vegetation; reseeding native grasses and replanting native shrubs and trees; reintroduction and protection of native fauna

MOUNTAINS

Degraders: Forest clearance for agriculture, dams and roads; soil erosion; natural disasters such as avalanches, landslides and floods

Restorers: Tree planting, better planning of infrastructure, use of low-impact farming techniques such as agroforestry

PEATLAND

Degraders: Peat extraction; drainage for agriculture, infrastructure, mining and fossil fuel exploration; fire, overgrazing, pollution

Restorers: Re-wetting, conservation

FARMLAND

Degraders: Overgrazing and soil erosion; monocultures; removal of hedges and trees; pollution from fertilisers and pesticides

Restorers: Crop rotation with more diverse crops, including trees and livestock grazing on cropland after harvest; use of natural fertilisers and pest control

CITIES

Degraders: Urban sprawl; waste and emissions from industry, traffic and homes

Restorers: Stricter planning laws; clean-up of waterways and former industrial sites; tree planting and creation of green space and urban wetlands

But while very possible, active restoration brings risks if done unscientifically. Different solutions are needed in different places (see "How to restore an ecosystem", previous page).

The headline target of the Decade of Ecosystem Restoration is to restore 3.5 million square kilometres of land over the coming decade – slightly more than the size of India, or just over 2 per cent of the world's land surface. That is an ambitious target and won't come cheap. According to the United Nations Environment Programme, the upfront cost is about $1 trillion, no small change in these covid-affected times, although it is an investment with a high rate of return.

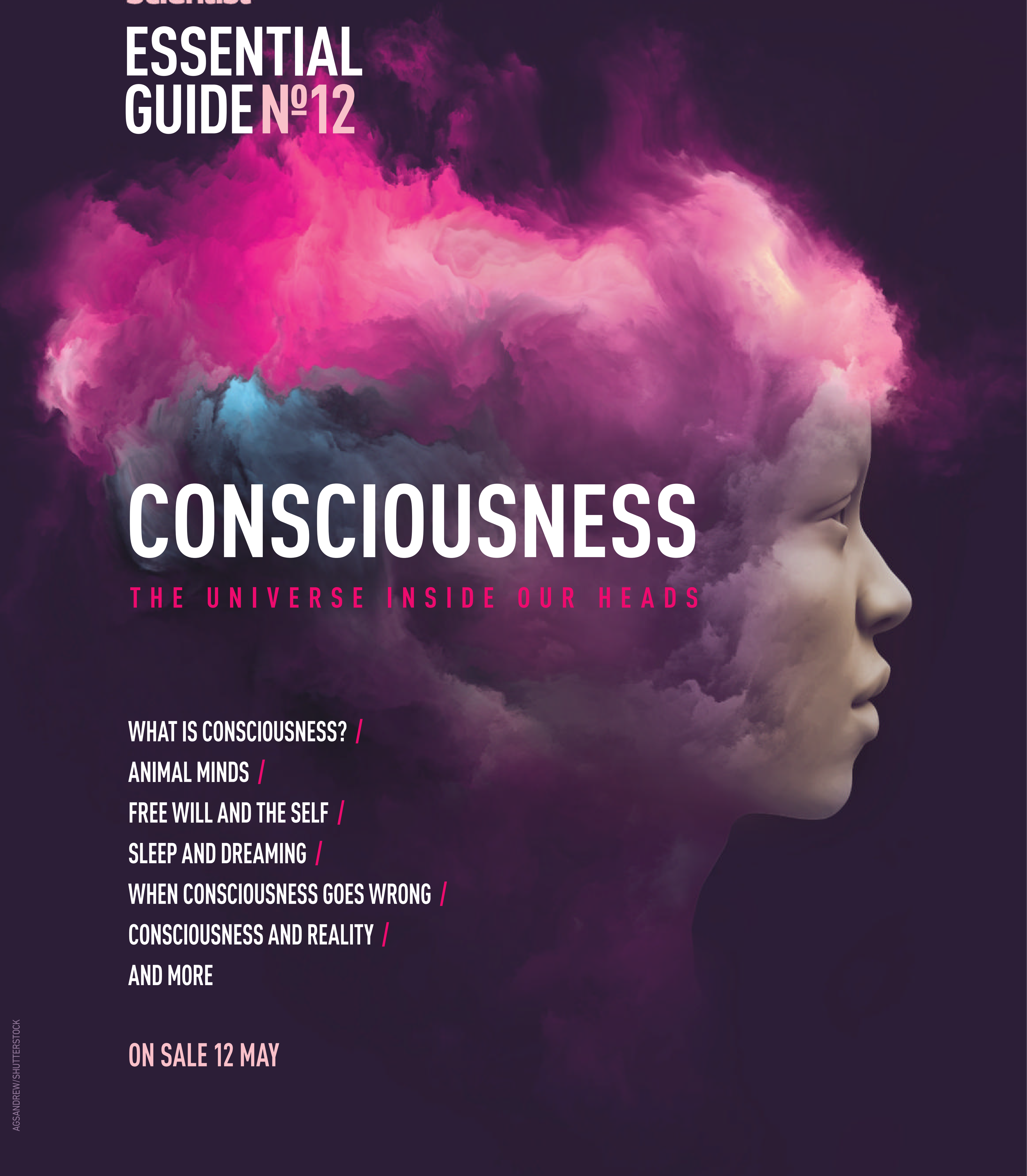
On paper, at least, it is already in the bag. Annelies Sewell at the Netherlands Environmental Assessment Agency in The Hague and her colleagues totted up commitments to existing restoration projects in 115 countries, encompassing plans to increase protected areas; restore and improve forests, croplands and grasslands; and more. They found that this adds up to about 10 million square kilometres, roughly the size of China or just under 7 per cent of world land surface area (see graphic, page 94).

Land conservation and restoration can help solve multiple environmental challenges, but "it won't fix them on its own", says Sewell. Hence a second pillar of conservation efforts that is going on right now: the negotiation of a new suite of biodiversity goals, replacing the Aichi targets, to run alongside the Decade on Ecosystem Restoration. Together, these mean the 2020s will be make-or-break time.

Despite Aichi's overall failure, another lesson of the past decade is that, where governments and other groups commit to protecting biodiversity, change can happen. "I don't want to sugar-coat this because this was not a great result," David Cooper, deputy executive secretary of the CBD, told the World Biodiversity Forum 2021. "But where serious actions have been taken, for example to reduce the rate of deforestation, to improve the state of fisheries, to prevent extinctions where we know the cause, significant progress has been made."

Ultimately, success or failure will depend on progress in another key area: climate change. But that works two ways – conserving biodiversity and restoring ecosystems will have positive knock-on effects for the climate. Land-use change and increased plant cover can deliver up to a third of the reduction in greenhouse gases that we need. There needs to be synergy, with biodiversity initiatives, efforts to combat climate change and other international programmes such as the UN Sustainable Development Goals converging on the ultimate target: harmony with nature by 2050.

There are still huge obstacles. But at least the right noises are being made. And crucially there is still time, just, to manage the pivot from the Great Acceleration to a Great Restoration, an era when humanity learns again to live sustainably and in harmony with nature. Life will no doubt weather the storm of a sixth mass extinction in some form, as it did five times before – but our survival, and the survival of the bounteous beauty of life on Earth as we know it, may depend on changing the weather. ▮



New Scientist

ESSENTIAL
GUIDE №12

CONSCIOUSNESS

THE UNIVERSE INSIDE OUR HEADS

WHAT IS CONSCIOUSNESS? /
ANIMAL MINDS /
FREE WILL AND THE SELF /
SLEEP AND DREAMING /
WHEN CONSCIOUSNESS GOES WRONG /
CONSCIOUSNESS AND REALITY /
AND MORE

ON SALE 12 MAY

AGSANDREW/SHUTTERSTOCK

New Scientist

ESSENTIAL GUIDE №11

LIFE ON EARTH

HOW DID LIFE ON EARTH GET STARTED? HOW DID IT EVOLVE INTO THE WONDROUS, TEEMING BIOSPHERE WE SEE TODAY – AND HOW DO WE BEST PRESERVE IT?

THE STORY OF LIFE ON OUR PLANET IS, AS FAR AS WE KNOW, UNIQUE. DELVE INTO MORE THAN 3 BILLION YEARS OF EARTH'S HISTORY AND SURVEY THE LIVING WORLD TODAY WITH THIS 11TH *NEW SCIENTIST* ESSENTIAL GUIDE. TOPICS INCLUDE:

① How life began

② From simple to complex cells

③ Evolutionary leaps and mass extinctions

④ Plant, animal and fungal wonders

⑤ The state of biodiversity today

£9.99

9 772634 015019 11